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APPLICABILITY OF ERTS-1 TO MONTANA GEOLOGY

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16. Abstract For interpretation and annotation using the standard methods of photogeology we favor 1:500,000 scale paper prints for Band 7 supplemented by Band 5. Late Autumn imagery provides the advantages of topographic shadow enhancement and low cloud cover. Mapping of rock units was done locally with good results for alluvium, basin fill, volcanics, inclined Paleozoic and Mesozoic beds, and host strata of bentonite beds. Folds, intrusive domes, and even dip directions were mapped where differential erosion was significant. However, mapping was not possible for Belt strata, was difficult for granite, and was hindered by coniferous forest compared to grass cover. Expansion of local mapping required geologic control and encountered significant areas unmappable from ERTS imagery.

Annotation of lineaments (fracture-controlled lines) provided much new geologic data. By extrapolating test site comparisons we infer that 27 per cent of some 1200 lineaments mapped for western Montana represent known faults. The remainder appear to be localized mainly by undiscovered faults and sets of minor faults or joints. Our map approximates a detailed map of high-angle faults and can be used in the same way for such tectonic purposes as domain analysis, geothermal exploration, and the identification of tectonic hinge lines in petroleum exploration. No striking relationships of lineaments to hydrothermal ore were seen for Montana.

There is no tectonic map of Montana at a scale comparable to that of the state geologic map (1:500,000). A statewide lineament map would be a useful substitute, providing many of the benefits at a few per cent of the cost, with a saving of many years in compilation time. It would also be a valuable guide to compilers of tectonic maps. Our discovery of errors in the state geologic map suggests limited use of ERTS imagery in revising that map. The geologic benefits of ERTS imagery for similar but less studied areas elsewhere in the world would be many times greater than those cited for Montana.

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PREFACE

The primary objectives of the investigation were to develop and evaluate tectonic and photogeologic mapping methods for both forested and sparsely vegetated terrain, and to test applications for Montana. This involved the study of imagery for different seasons, spectral bands, and print scales, the laying and study of mosaics, experimental use of 70mm positive transparencies, and optical color enhancements of multispectral 70mm chips. Detailed evaluations required the compilation of geologic truth maps, the use of underflight photographs, and field checks. We conclude that visual geologic interpretation of ERTS imagery for our area is best done using 1:500,000-scale paper prints of late Fall imagery for Band 7 supplemented by Band 5. Forest cover impedes but does not preclude photogeologic interpretation; significantly more geologic information can be extracted from imagery of grass-covered areas.

Although identification and mapping of major rock units, folds, and intrusive domes could be done locally with reliability and precision (even to the extent of revealing errors in the state geologic map), wide-scope photogeologic mapping by operator image interpretation would be discontinuous and could not be accomplished for large areas underlain by strata of the Precambrian Belt Supergroup. With local exceptions such mapping would not be advantageous for Montana, which has already been covered by a combination of detailed and reconnaissance geologic mapping. However, this approach would yield valuable photogeologic reconnaissance information for less studied areas of generally similar geology, latitute, and climate elsewhere in the world.

A wealth of new geologic information was gained from an ERTS lineament map of western Montana prepared by annotation of fracture-controlled geologic lines. Careful evaluation indicates

that this new type of geologic map is an inexpensive substitute for a compiled tectonic map in several important respects. Its lines, which represent mainly high-angle faults and sets of fractures (faults or joints), may be used in tectonic map preparation to locate probable unmapped faults, to identify structural domains, to analyze fracture patterns, and to guide geothermal and petroleum exploration. The relationship of ore to lineaments in western Montana was poor, suggesting only limited application of ERTS lineaments in a search for additional hydrothermal ore deposits.

We recommend that geologists use an ERTS lineament map to gain new tectonic perspectives and insights. Our lineament map of western Montana is being expanded to cover eastern Montana, and arrangements have been made for its publication by the Montana Bureau of Mines and Geology. Extensions of this investigation now in progress relate mainly to lineaments. They include domain delineation by rose diagram analysis, evaluation of illumination bias using plastic relief maps, possible advantages of edge enhancement on the scanning microdensitometer for lineament mapping, and the relative importance of Precambrian basement structure in the development of lineaments.

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Introduction

Montana, with its wide variety of geologic terranes, topography, climate, and vegetative cover (Figures 1, 2, 8, and 9), is ideally suited for feasibility studies using ERTS imagery and classic photogeologic methods. On the continental divide and to the west is rugged mountain country interrupted by a number of small Cenozoic basins; bedrock consists mainly of metasedimentary strata of the Belt Supergroup cut by a number of granitic plutons. East of the divide are the Montana plains, underlain by essentially horizontal Mesozoic and early Tertiary sedimentary strata, which are locally deformed near areas of mountain uplift out in the plains and along the Rocky Mountain front. In the latter areas Paleozoic carbonates are abundant. Significant areas of Precambrian basement rock occur in southwestern Montana, and volcanic rocks of Cretaceous and Cenozoic ages occur at a number of places in the western half of the state. The front of the mountains coincides with the edge of a foldbelt marked by numerous thrusts and overthrusts. Zones of strike-slip faulting form structural breaks of northwesterly trend through the central part of the western half of the state (Lewis and Clark Lines or Montana Lineaments).

The plains are grass covered, and their river breaks, mountain uplifts, and flanking mountains have a sparse coniferous forest or brush cover controlled by the semiarid climate. The mountains west of the continental divide, on the other hand, are heavily covered by coniferous forests in response to the more moist climate.

Our investigation covered the feasibility of using ERTS imagery for tectonic mapping and analysis (mainly lineament studies) and for photogeologic mapping (rock unit recognition and delineation) in both heavily forested and sparsely vegetated terrain. This involved determination of the most useful imagery in terms of spectral bands, season of the year, and print scale, evaluation of optical color enhancement methods, development of the most effective techniques of annotation,

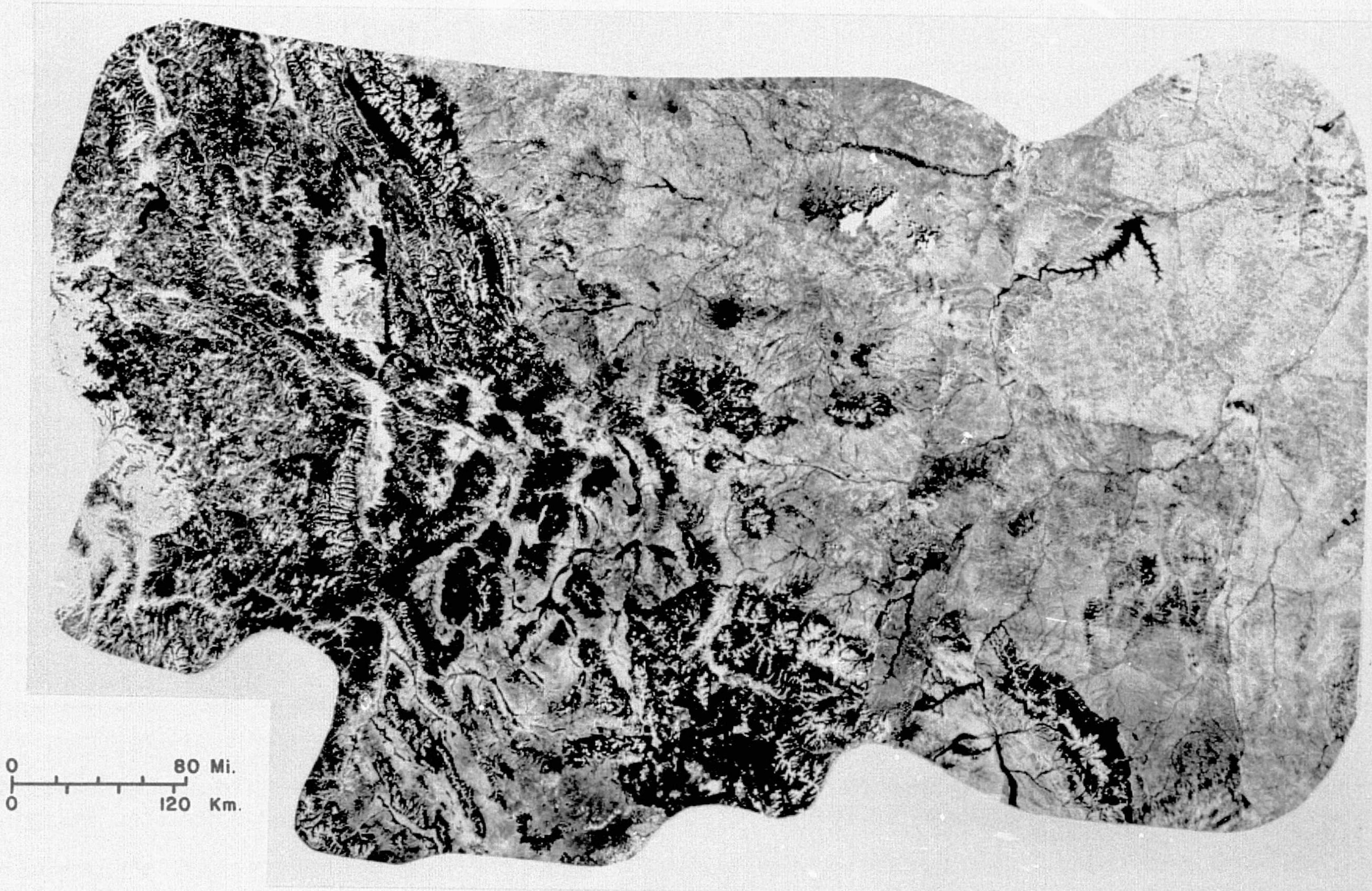


Figure 1. Red band ERTS mosaic of Montana and adjacent areas showing contrasts in topography and vegetation. Dark areas are coniferous forests except for irrigated lands along rivers. See Figure 2 for geographic details. Prepared by USDA, Forest Service, Division of Engineering, Missoula, Montana, from 1972 late summer and fall imagery. Original scale 1:850,000.

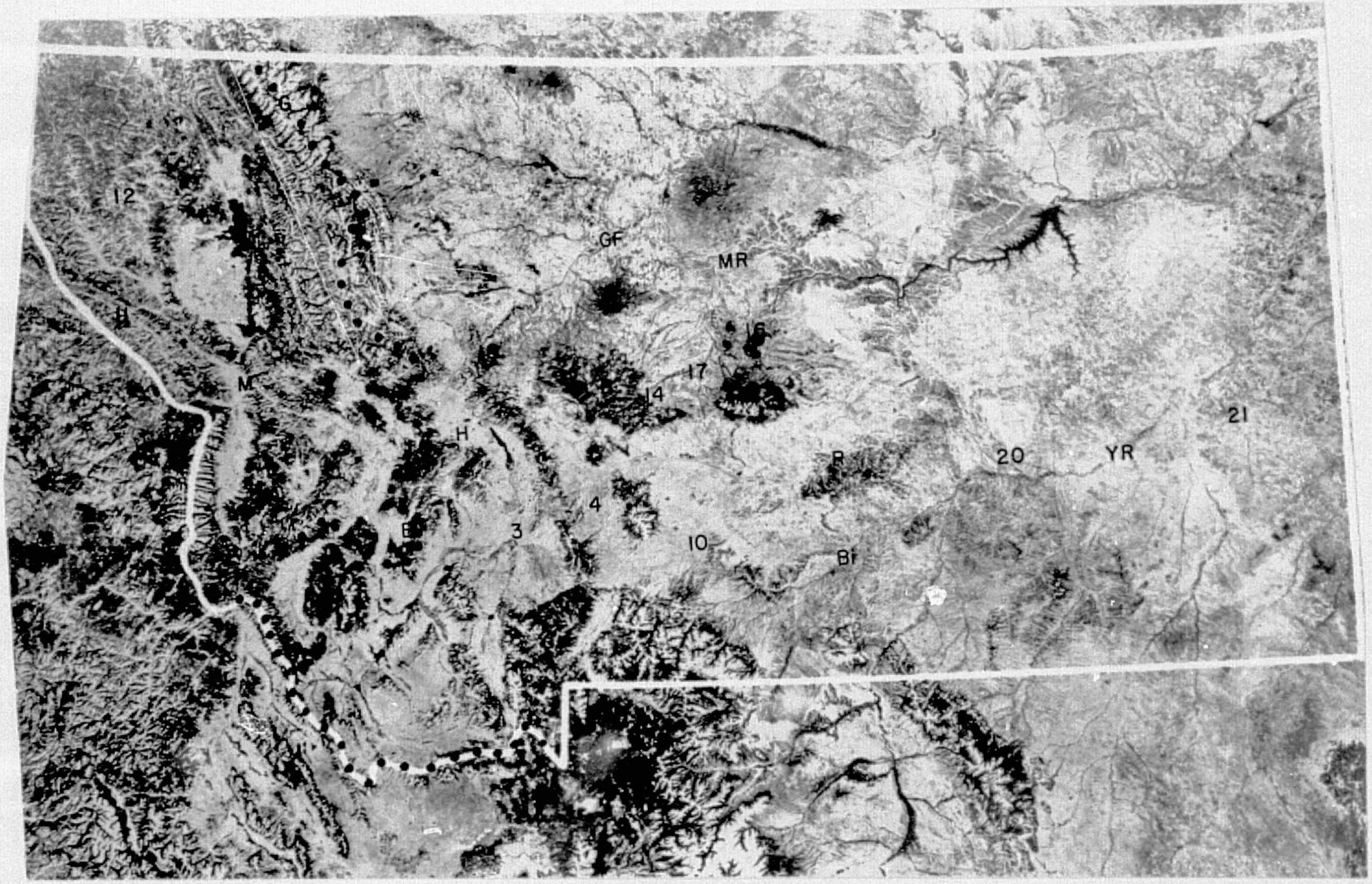


Figure 2. Index mosaic of Montana (red band NASA-SCS mosaic, Fall 1972). Dotted line locates continental divide. Numbers show locations of text figures. Letters identify the following places and features: Bi - Billings, BS - Big Snowy Mts., Bu - Butte, G - Glacier Park, GF - Great Falls, H - Helena, LB - Little Belt Mts., M - Missoula, MR - Missouri River, R - Roundup, Y - Yellowstone Park, YR - Yellowstone River.

and the evaluation of photogeologic and tectonic results using geologic map truth, underflight photo-interpretation, and field checking. Most of the more detailed studies were carried out in the areas of three designated test sites (see Appendix), for which high altitude multiband and color infrared U-2 photography was provided by the NASA-ERAP program. Applications of ERTS imagery interpretation to the preparation of a tectonic map for Montana and revision of the state geologic were considered. A small part of the investigation covered possible applications to the investigation of economic mineral resources (bentonite, petroleum, and hydrothermal ore deposits).

Investigation was a team effort. In addition to the authors, co-investigators were R. Berg and W. Johns of the Montana Bureau of Mines and Geology. C.J. Vitaliano of Indiana University was a consultant for Test Site 354D, and the late W.J. McMannis of Montana State University was a consultant on statewide evaluation of applications and for a tectonic mapping project in the Crazy Mountains Basin area. We acknowledge the contributions of R. Flood, K. Hawley, and L. Wackwitz, who served as research assistants. D. Comstock and personnel of the U.S. Forest Service Division of Engineering provided some photolab services and laid the first ERTS mosaic of Montana as a cooperative project (Figure 1). Our file of ERTS imagery for the state and high altitude aerial photography for test sites has drawn visits from many professional people in a variety of disciplines, including geology, soil science, hydrology, forestry, range management, wildlife biology, geography, and land use planning. These contacts, which are continuing, have not only allowed visitors access to imagery, but have been stimulating to us as well.

Interpretation Methods

Most of our work involved the annotation and interpretation of black and white paper prints at a scale of 1:500,000, using conventional photogeologic techniques. ERTS mosaics at a scale of 1:1,000,000 were used for regional studies. We experimented with annotation using the camera lucida method with 70 mm transparencies under a binocular microscope (Wild M7) and with 1:1,000,000 scale prints on a Zoom Transfer Scope. These methods were not as convenient or effective as direct study of the larger prints, but they allowed supplemental annotation for different spectral bands and times of the year without preparation of enlargements. The binocular microscope, used over a bright light table, allowed evaluation of fall scenes for which undodged standard paper prints were very dark and for which 1:1,000,000 scale positive transparencies were lacking. Experimentation with optical color enhancement using a Spectral Data Corporation multispectral viewer (Model M64) involved recording images by 35 mm camera on Ektachrome EHB film for later projection and study. High altitude aerial photographs from U-2 flights provided a bridge between annotations of satellite imagery and ground truth in the form of geologic maps and field checks for selected areas designated as test sites (see Appendix).

Print Scale and Preparation

First attempts at annotation using standard 1:1,000,000 scale prints proved unsatisfactory because the print scale was too small for the detail we wished to show, and because of the very dark tone of the late fall prints. Both problems were solved by using 70 mm negatives supplied by NASA to prepare enlargements at scales of 1:500,000 and 1:250,000. Very dark negatives for late summer were replaced with

lighter negatives exposed from 70 mm positive transparencies in a contact printer. Prints at a scale of 1:500,000, which not only provided necessary space for annotation, but also matched the scale of the Geologic Map of Montana, proved ideal for most of our purposes.

Seasonal Effects: Sun Elevation and Vegetation

We evaluated imagery covering the periods late August through November, 1972, and late March through June, 1973, for seasonal effects affecting photogeologic interpretation. Although sharp in detail, imagery for late summer of 1972 was disappointing. With low shadow relief from sun elevations of 40-50°, certain topographic features important for photogeologic interpretation were difficult or impossible to see, making it necessary to rely on the less effective recognition elements of tone and drainage pattern. Images for late fall (sun elevation 20-30°) were much more satisfactory because landforms are sensitively revealed by topographic shadowing (Figure 3) and tonal differences are at least as useful as for late summer.

Comparison of imagery before and after autumn leaf drop did not reveal any striking effects useful in photogeologic interpretation, but comparison of growing season imagery (June) with earlier or later imagery suggests enhancement of tonal contrast for grassy areas underlain by tilted sedimentary rock units (Figure 4). However, prevailing cloud cover during June minimized the utility of this enhancement, which does not apply to forested areas in any case. Flood plains with deciduous trees and brush, or with irrigated fields, show the best tone contrasts during the growing season.

Effects of Climate and Vegetation

Except in some grass-covered valley areas, Montana west of the continental divide has a climate wet enough to support dense coniferous forests which grow on deep residual soils (Figure 1). Bedrock is poorly exposed in most of this region and conventional geologic map-

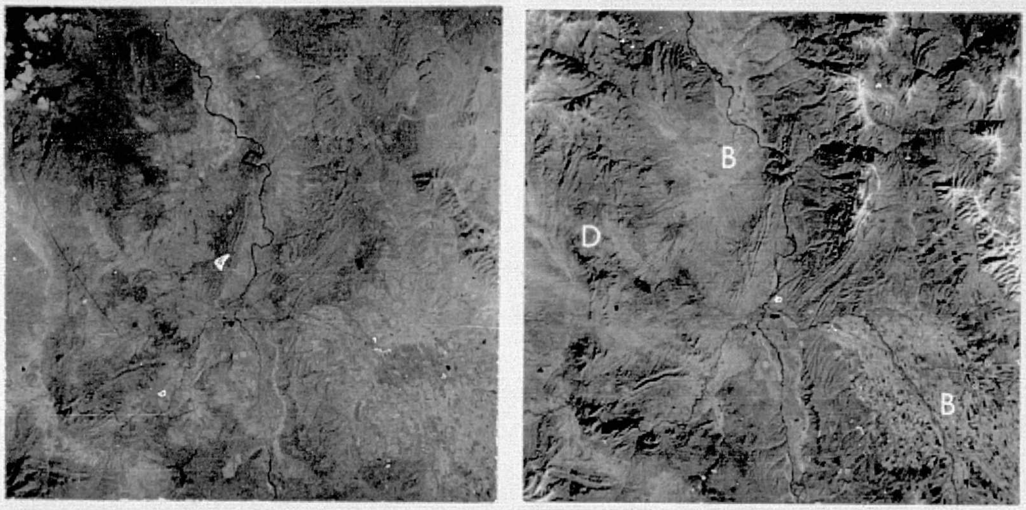


Figure 3. Three Forks area, showing headwaters of Missouri River (center). Note parallel ridge and valley topography representing inclined sedimentary strata partly covered by Cenozoic basin fill (B). Plunging folds are visible above D. Figure 3-1 (left), imaged 26 August 1972, indicates weak shadow modelling from high sun angle of 48° (ID# 1034-17461-7). Figure 3-2 (right) imaged 6 November 1972, shows strong enhancement of topography from a low sun elevation of 25° (ID# 1106-17465-7). Width of scene is 46 miles (74 km).

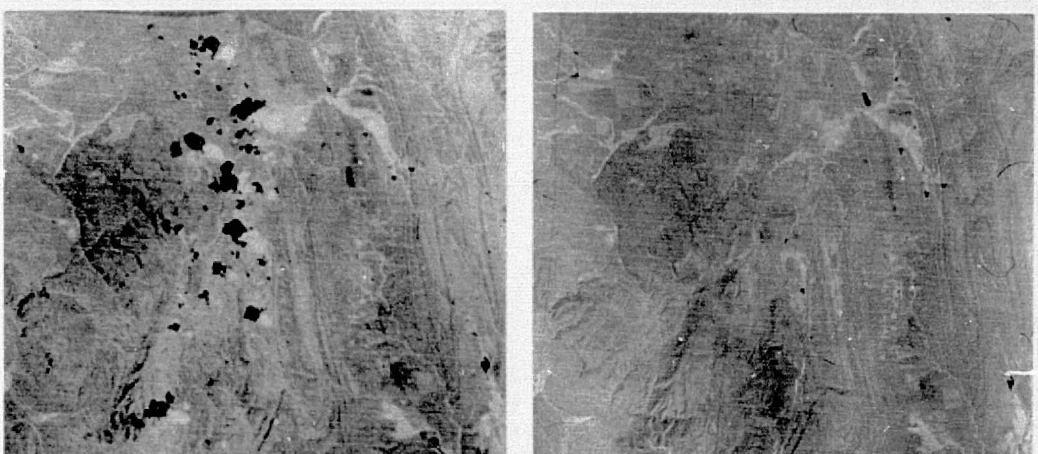


Figure 4. Enhancement of tone contrast by vegetation on grass-covered noses near Ringling (see also Figure 15). Figure 4-1 (left) for 28 June 1973, shows strong tone banding (ID# 1340-17463-7). Figure 4-2 (right) for 22 May 1973, shows much weaker tone banding (ID# 1303-17412-7). Width of scene is 24 miles (39 km).

ping on the ground is a difficult and uncertain task. Structural complexity and the subtleties of stratigraphic correlation within the Precambrian sedimentary formations of the Belt Supergroup, which outcrop in most of the region, add to the burdens of the field geologist. ERTS imagery is similarly difficult to interpret in this region. Most tonal variation appears to be more nearly related to questions of forestry than to geology. The only topographic expressions of geology in most of this region are in the form of lineaments apparently related to faulting, and certain landforms representing surficial deposits such as glacial moraines and floodplains. Upturned edges of folded sedimentary beds are not topographically expressed as strike ridges and valleys, and outlines of igneous intrusives or volcanic fields are generally difficult or impossible to see. In contrast, Montana east of the divide, which is drier and predominantly grass-covered, is favorable for photogeologic interpretation, showing tone contrasts locally and fairly good topographic expression of differentially eroded strata overall.

Geologic Utility of the Different Spectral Bands

Multispectral scanner Band 6 and especially Band 7 (reflected infrared radiation) provide the most suitable imagery for our purposes because they most clearly reveal topographic detail. Contrasts between most naturally occurring vegetation are minimized, and coniferous forests are imaged in a tone light enough to allow shadow relief to be seen. Band 5 (red band), which emphasizes variations in plant cover, is frequently a useful supplement to Band 7. This is especially true for summer imagery with low shadow relief, on which the dark tone of forest patches in Band 5 is a clue to the existence of northerly facing slopes. Some rock units in the semi-arid regions east of the continental Divide are tonally distinguishable in Band 5 because of contrasting vegetative cover, but they are generally recognizeable in Band 7 imagery also.

We have found Band 4 (green band) imagery to be much less useful than the others for photogeologic interpretation. Detail is less sharp because of haze effects, and the contrast range is limited. However, in Band 4 imagery shallow areas of larger lakes are clearly

marked by the light tone of visible bottom. This is particularly noticeable for Flathead Lake at Polson Bay at the south and in the delta area at the north. At the time of lowest water level in the Spring, the tone differences related to water depth are seen also in Band 5 imagery, and it would appear that a rough bathymetric map could be made for parts of the lake using a scanning microdensitometer (ID# 1270-17582, 19 April 1973).

Color Enhancement

Considerable effort was expended in attempting to use optical color enhancement as an aid to geologic interpretation of ERTS imagery. Success was not nearly as frequent as failure and the value of the results has not been commensurate with the effort expended. Black and white enlargements of Band 7 (infrared) imagery are as useful as color enhanced imagery for most applications we have attempted.

Operation of the equipment was a major obstacle. Endless adjustment and tinkering seemed necessary to get scenes in acceptable registry and we generally settled for two-band enhancement rather than spend the time to get three or four images projected simultaneously. Many of the equipment problems were eased considerably by projecting the images in larger format directly onto a wall screen, bypassing the internal mirror in the equipment.

First attempts at color enhancement consisted mostly of attempts to simulate the natural colors of the scenes. Results were pleasing aesthetically but not notably helpful in geologic interpretation. Somewhat better results were obtained by pursuing the opposite approach, obtaining an unnatural and jarring color scheme. This seemed to have the effect of encouraging people to visualize new relationships instead of simply trying to recognize familiar places. But the effect was more beneficial from a psychological than from any other point of view. Jarring color schemes are not much more revealing of bedrock distribution than natural ones.

Long hours were spent in methodically making changes of filters on a particular scene, looking as systematically as possible for some combination that might reveal certain kinds of bedrock. There were such combinations but the kinds of bedrock they revealed were such things as limestone ridges and unconsolidated valley fill that are visible on the black and white enlargements. No color combinations were found that clearly revealed bedrock distributions that were not also apparent on single-band black and white enlargements.

The best success with color enhancement was in an experiment with a mosaic covering eastern Montana. We projected diapositive copies made from the NASA-SCS ERTS mosaic for Bands 5 and 7 (late summer-fall, 1972). Some outcrop patterns surrounding large dome uplifts were strongly emphasized by color enhancement and much easier to see than in black and white prints. However, over much of the projection area, vegetation patterns unrelated to bedrock geology controlled the color distribution. A similar mosaic enhancement for western Montana was dominated by the influence of vegetation and not useful for photogeologic purposes.

Photogeologic Recognition Criteria

Our photogeologic studies involved the experimental mapping of fracture lines (lineaments), folds, domes, and dip directions, as well as the delineation of different rock units occurring over wide areas. In these studies, landform was almost always the most important recognition element. Drainage pattern and density were commonly next in importance, and tone was usually the least helpful of the common recognition criteria. The association of lakes with erosional and depositional topographic features of glacial origin was used to delineate areas of glaciated terrain. Specific recognition criteria for different geologic structures and rock units are discussed in later sections.

Annotation

Our annotations were done on transparent acetate overlays with overhead projector pens and water soluble ink. Cartographic control was established by tracing major streams in blue. Different geologic features were distinguished through the use of different colored lines. Corrections could be made after erasing with a damp cloth. Final annotations were protected by spraying with a plastic varnish. Though very simple, this system works quite efficiently, and it allows easy comparison with ground truth maps at image scale.

Lineament Mapping

The most common and widespread geologic features visible on ERTS imagery of Montana are straight geologic lines here designated as lineaments. We put a great deal of effort into mapping and evaluating these features, which are believed to be controlled mainly by lines of fracture. ERTS lineament maps are a new and inexpensive type of tectonic map, with a potential not fully understood and uses not fully exploited. Definition, recognition, and annotation of ERTS lineaments are discussed below, as are operator and illumination bias, compilation of ground truth data, and our evaluation of the geologic significance of lineaments and lineament maps.

Definition and Recognition

The term lineament has had several different usages, some related to major tectonic features and some to features seen in aerial photographs; most uses imply straightness. In this report, lineament, where not otherwise qualified, refers to an ERTS lineament. Our use is close to that proposed by Lattman (1958) for aerial photomosaic lineaments, namely fracture-related linear trends of topography, soil, vegetation and straight stream segments. Lines caused by tilted bedding and folds are excluded in all cases where those origins are apparent. We mapped lineaments which range in length from about 2 miles (3 km) to 50-90 miles (80-145 km). Most of them would be regarded by Hoppin (1974) as linears (less than a few tens of kilometers in length), but those longer than 100 km qualify as lineaments according to his definition.

Visual recognition and annotation of lineaments using conventional photogeologic methods obviously involves considerable subjective judgment with corresponding risk of operator bias and error. To reduce these factors to a practicable minimum, we defined three categories of lineaments: straight escarpments, straight segments of streams or valleys

including minor valleys alignedon opposite sides of a drainage divide or trunk stream, and straight tonal boundaries unrelated to normal stratigraphic contacts (Figure 5). Some lineaments change character along their length passing from escarpments to tonal boundaries or straight stream valleys. All aligned features were annotated along the route of lowest topographic expression - along the base of an escarpment or a straight stream valley, never on ridge crests. Linear features corresponding to upturned edges of sedimentary strata were not annotated if their nature was apparent.

No difficulty derived from confusion of bedrock lineaments with cultural features such as transmission lines or agricultural patterns. Conceivably this could become a problem in areas more densely populated than Montana.

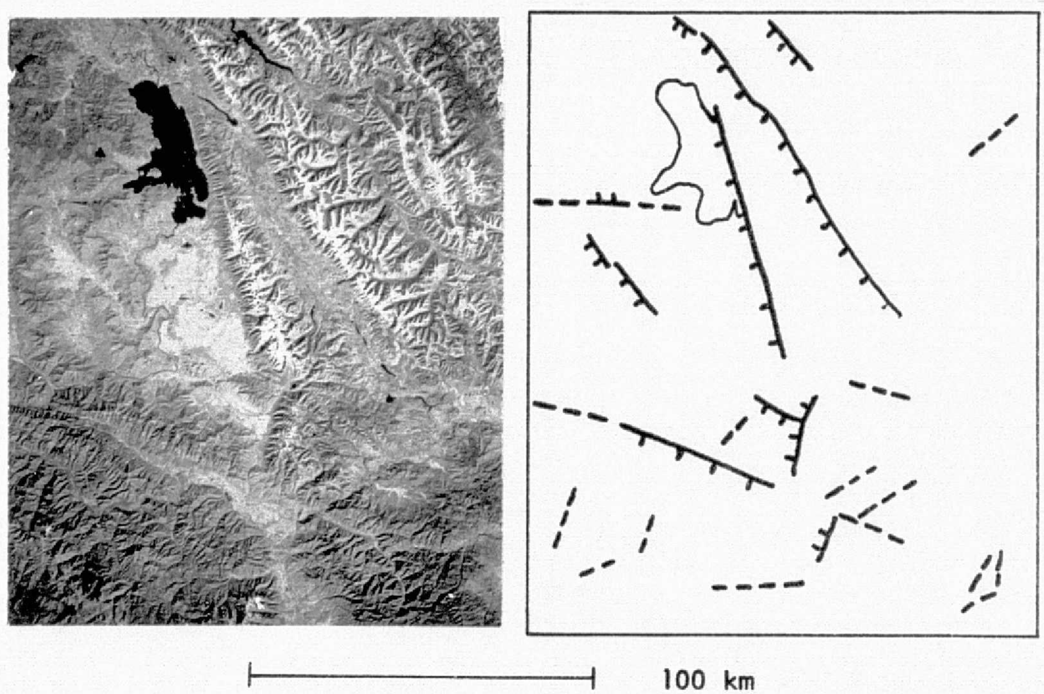


Figure 5. ERTS scene showing simplified lineament annotation compatible with small scale of picture. Figure 5-1 (left) is a Band 6 print of the Missoula-Flathead Lake area showing excellent topographic shadow modelling. (3 October 1972, ID# 1072-17571). Width of scene is about 93 miles (150 Km). In Figure 5-2 (right), only the more bold lineaments have been annotated. Hachured lines are scarps; dashed lines are straight canyons and streams.

Annotation and Map Compilation

Annotation was done on transparent acetate sheets over 1:500,000 scale prints, using different colors for different operators. Copies of overlays by different operators were registered for comparison, and an edited final overlay prepared for each scene. Final overlays were traced onto a base map using main streams for control (Figure 6). In the compilation process any discrepancies in the areas of 40 percent sidelap were reconciled.

Operator Bias

Insurance against operator bias was provided by having several operators (five for most of the image scenes) prepare annotations (which included elongate folds and circular structures as well as lineaments). Lines shown by only one operator were discarded, and lines shown by only two were carefully re-evaluated.

Operator bias did appear, as had been expected, but there was relatively little operator error. Some operators were much more conservative than others in identifying and annotating geologic features but none had any problem distinguishing between geologic and cultural features and none drew lines where no apparent justification could be found. Neither was there a great problem with misplaced lines, all operators consistently drew their lines along geologically reasonable routes.

Experience suggests that adequate insurance against bias and error could be gotten by having two experienced operators prepare separate annotations for comparison, and that the few resulting discrepancies can be resolved by discussion during re-examination of the imagery.

Our evaluation of operator bias and error in conventional photogeologic interpretation of ERTS imagery led us to conclude that the problem is no different than with annotation of ordinary aerial photo-

graphs. We believe that any group of similarly competent geologists provided with the same imagery and the same background of local geologic knowledge would prepare a similar ERTS lineament map. Most ERTS lineaments have sufficient objective reality to be independently observable by different operators, and differences of opinion about their reality or continuity can ordinarily be resolved by agreeing to draw dashed or dotted lines along the places where uncertainty exists.

Our experience in working on ordinary aerial photographs and in geologic mapping on the ground has led us into uncertainties very similar to those encountered in study of ERTS imagery. It is often difficult to decide on the ground whether a fault exists and, if so, where it should be drawn and how to describe its movement. Our ERTS lineaments are as convincing to us as many faults or suspected faults that we have drawn on the ground and we have a similar level of confidence about their geologic reality.

Our decision to assemble annotations for individual scenes into a regional mosaic of lineaments rather than to use a regional mosaic of ERTS imagery for direct annotation was caused initially by problems in accurately fitting together a 1:500,000 scale mosaic. It proved advantageous in further reducing operator error and bias, however. All operators are tempted to carry a lineament as far as possible once they are satisfied of its reality. Annotation of an imagery mosaic presents numerous opportunities to yield to this temptation and extend lineaments to the point where they can be seen only with the eye of faith. Limiting operators to one scene at a time prevents this and insures that the very long lineaments really were independently observed on different image frames and their length not realized until the mosaic had been assembled. Forty percent sidelap provides an extra check on consistency.

Illumination Bias

Illumination of all imagery by the morning sun shining from a southeasterly direction is a problem that we cannot evaluate precisely. Most of our annotations seem to us to be biased in favor of topographic lines having a northeasterly trend, transverse to the illumination direction. We have frequently been surprised to see structural features trending in that direction clearly manifested in the ERTS imagery while others, with a northwesterly trend, are difficult or impossible to see. In parts of our area where good geologic maps exist, the lineament pattern seems to be weighted in favor of northeasterly trending structures and against those that trend northwest. This is strongly suggested by rose diagrams comparing lineaments and faults in northwestern Montana (Figure 12). However, the fact that all the imagery is illuminated from the same quadrant makes precise evaluation of this suspected bias quite impossible. It would be helpful to obtain imagery illuminated from another quadrant, and we believe this would add significantly to the geologic utility of ERTS imagery.

Utilization of Ground Truth Data

Structural and other ground truth data of several types were compiled on overlays at 1:500,000 for comparison with the lineament map (Figure 6). The first step was the utilization of small scale regional geologic and tectonic maps for comparison of major features. Source maps used were the Geologic Map of Montana (1955), the Tectonic Map of the United States (1962), and the Structure Contour Map of the Montana Plains (1955), supplemented by the Geologic Map of the United States (1974). Data compiled were faults (by type), and also the boundaries of tectonic provinces, Cenozoic intermontane basins, outcrop areas of Precambrian basement, volcanics, granite plutons of Cretaceous age, and shallow intrusive bodies of Tertiary age. Faults were

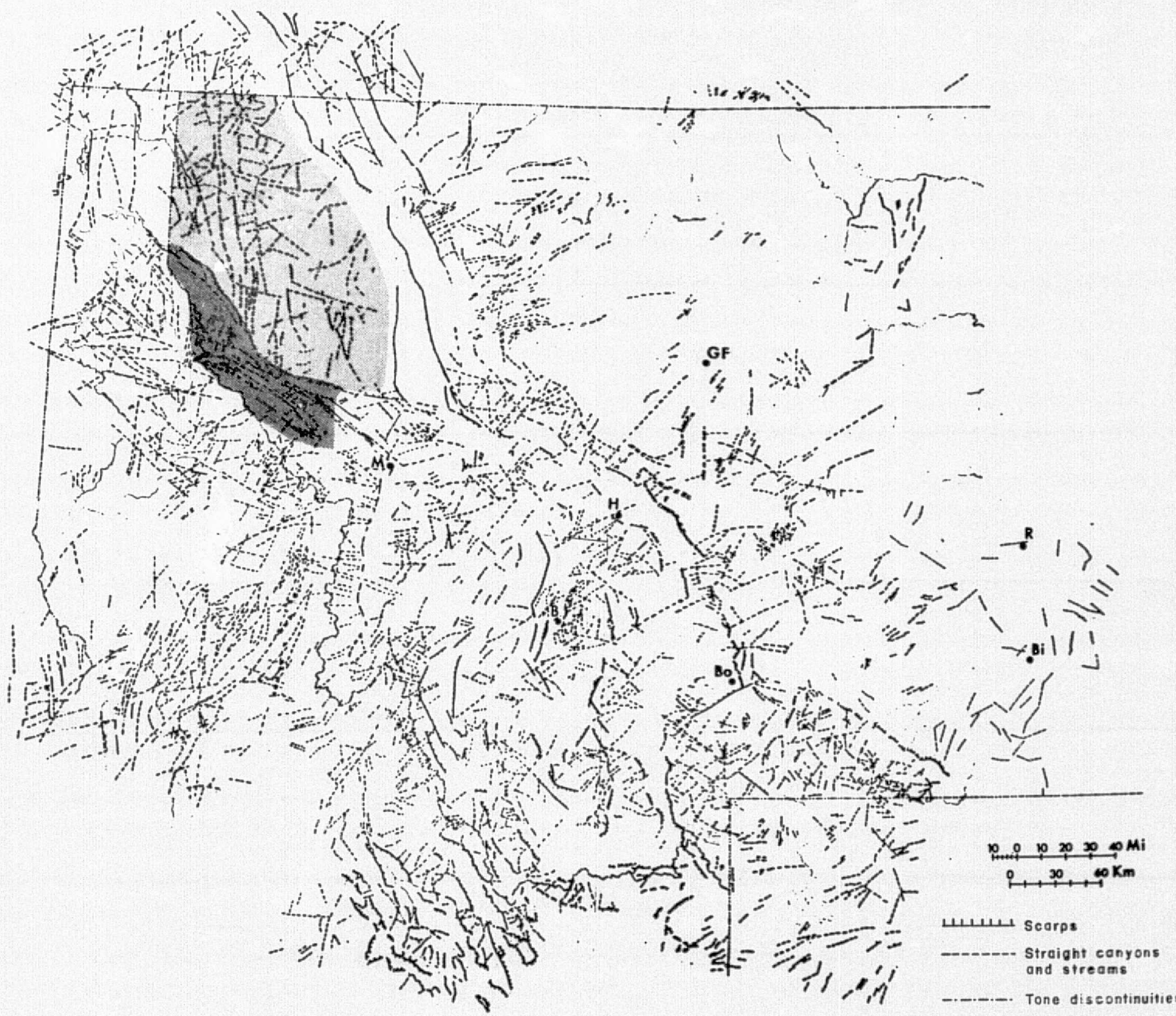


Figure 6. Detailed ERTS lineament map of western Montana and adjoining areas. Composite of 21 scene overlays, Band 7, late summer and fall, 1972. Original scale - 1:500,000. Shading delineates structural domains of Figure 12. B - Butte, Bi - Billings, Bo - Bozeman, GF - Great Falls, H - Helena, M - Missoula, R - Roundup. Full scale sepia or paper print is available at cost from Dept. of Geology, Univ. of Montana, Missoula, 59801.

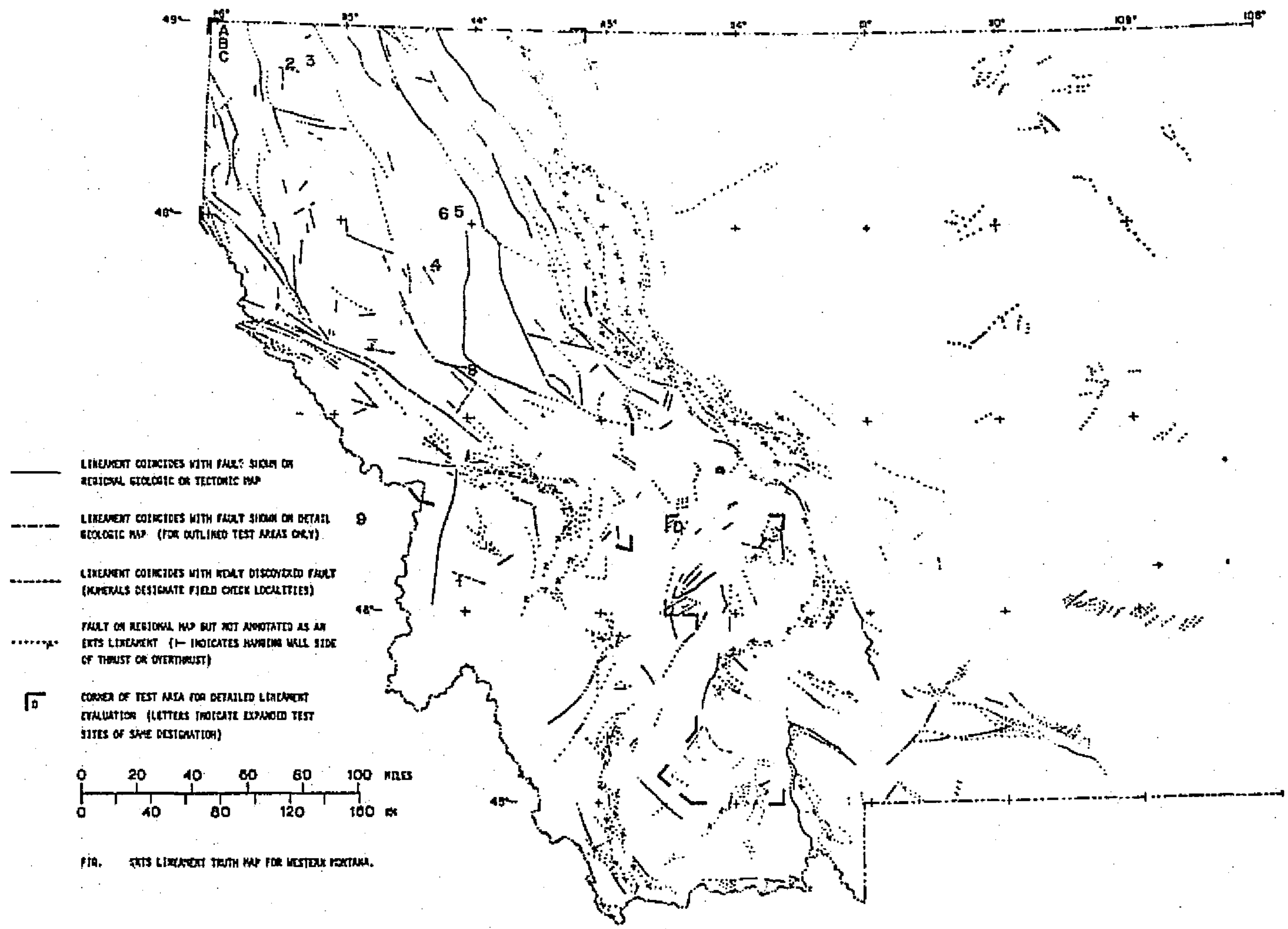
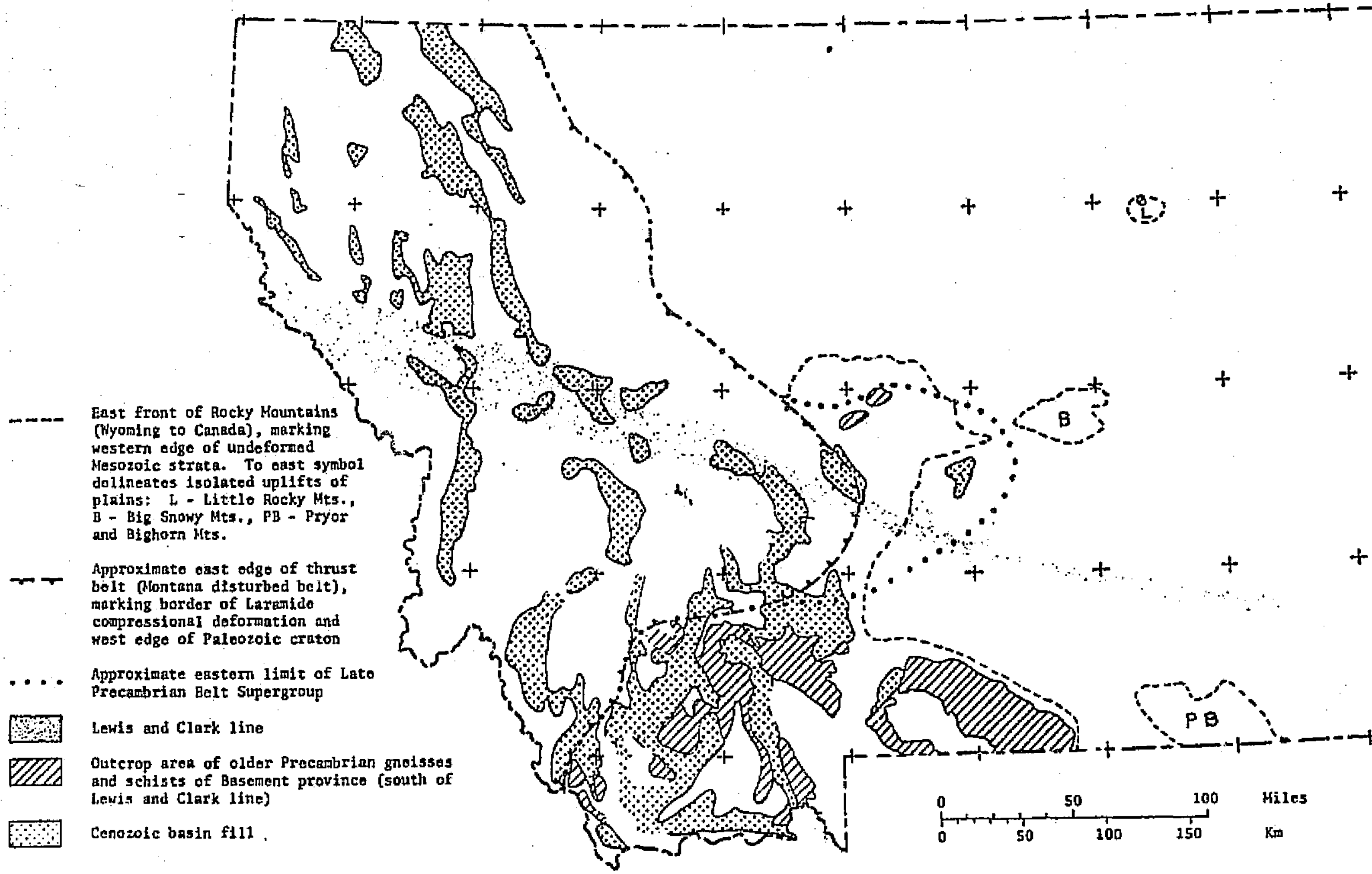
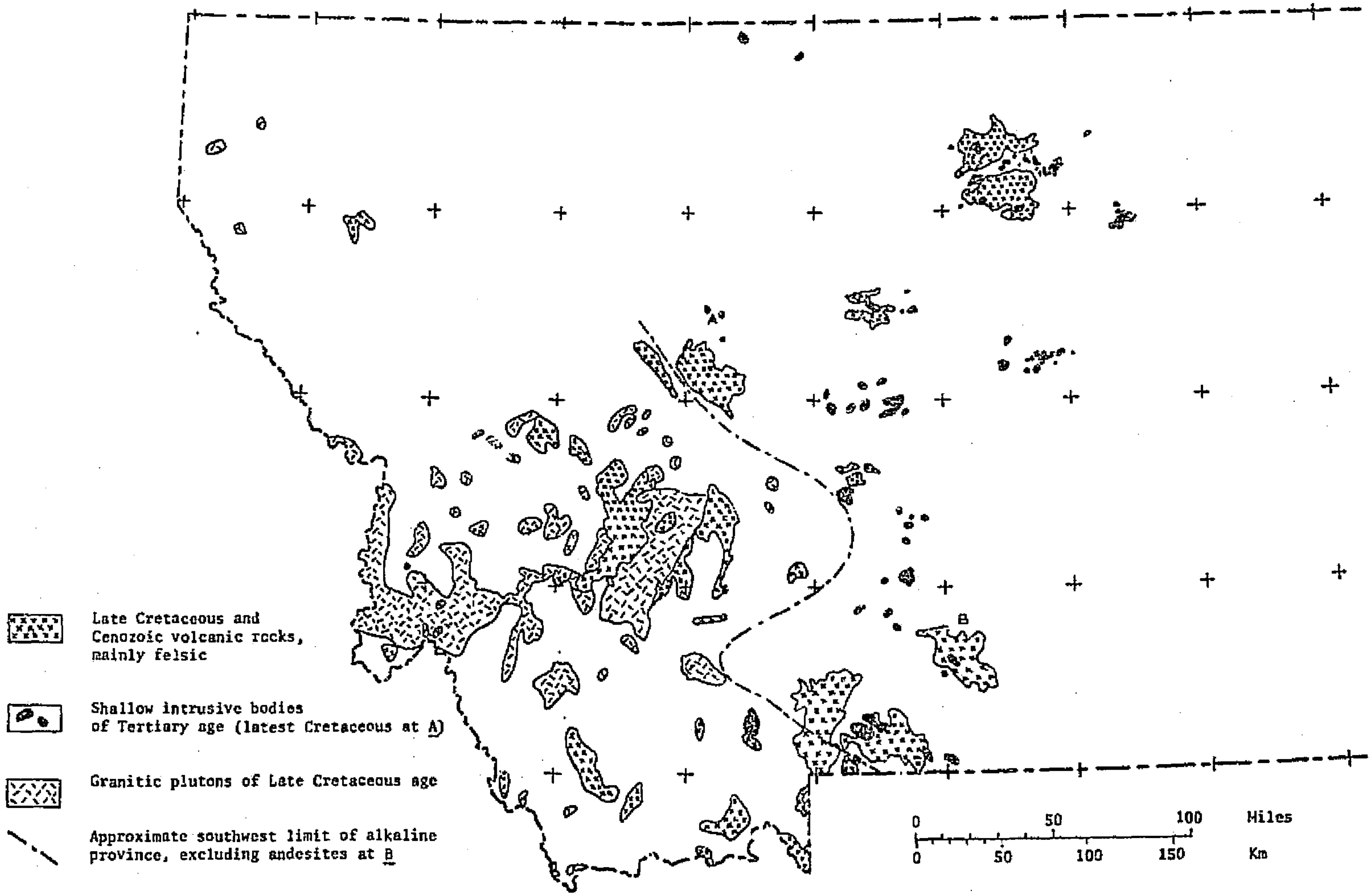


Figure 7. ERTS lineament truth map for western Montana. All except dotted lines coincide with lineaments in Figure 6. Any lineaments in Figure 6 not represented in Figure 7 are unevaluated lineaments which possibly represent unmapped faults or fracture trends. See film transparency of this figure in pocket. 1:500,000 scale original is available at cost as sepia or paper print from Department of Geology, University of Montana, Missoula, MT 59801. Superficial gravity glide faults south of Bearpaw Mts. are omitted from truth map.



Key tectonic and rock boundaries in Montana (modified from Geologic Map of Montana and Geologic Map of the United States).

Figure 8. Key tectonic and rock boundaries for western Montana. Compare with Figures 6 and 7 See film transparency of this figure in pocket.



Igneous rock bodies in Montana (modified from Geologic Map of Montana, Geologic Map of the United States, and Chadwick, 1972).

Figure 9. Igneous rock bodies in Montana. Compare with Figures 6 and 7. See film transparency of this figure in pocket.

compared to the lineament map at original scale (1:500,000) to develop a lineament truth map (Figure 7). All compilations were reduced to small size and printed in different colors on diazochrome transparencies for comparing different types of information with lineaments on the overhead projector (Figures 7, 8, 9).

A second step involved the preparation of much more detailed fault truth maps for a large area in northwest Montana (expanded Test Site 354 A, B, C) and a smaller area in southwest Montana (expanded Test Site 354 D) (corners of expanded sites are shown on Figure 7)*. This effort involved use of all appropriate published and unpublished geologic maps smaller in scale than 1:24,000. Maps were reduced in scale on a Kail reflecting projector supplemented by a Zoom Transfer Scope. Field checks and study of U-2 photographs were utilized to evaluate lineaments in parts of these areas.

Faults from the detailed compilations for the expanded test sites are delineated by separate symbols on the lineament truth map (Figure 7), which shows lineaments representing the following: 1) previously mapped faults from regional maps, 2) additional previously mapped faults from detailed maps, and 3) newly discovered and confirmed faults. Also shown are mapped faults not seen as lineaments in ERTS imagery. When Figure 7 is superimposed on Figure 6, one can locate a large number of unevaluated lineaments where no lines in Figure 7 match lineaments in Figure 6. Many of these may turn out to be newly discovered faults or fracture trends.

Lineament annotations done independently by W.J. McMannis for the Crazy Mountains Basin area in south-central Montana were evaluated by him using the state geologic map and a personal knowledge of ground truth (See Figure 10).

* See Figure 23 for complete outlines of expanded test sites.

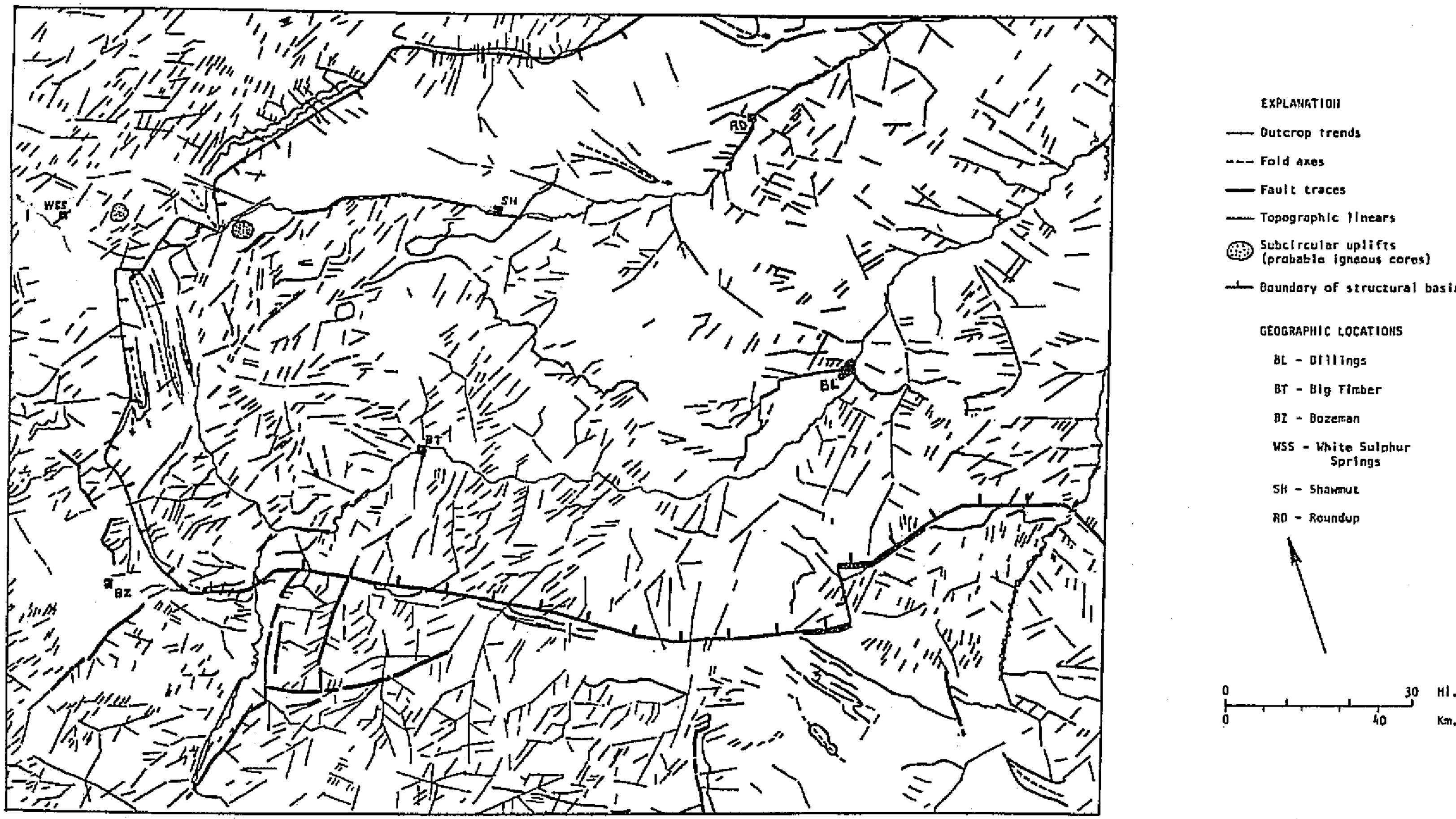


Figure 10. Lineaments (topographic linears), faults, folds, and outcrop trends drawn by W.J. McMannis from ERTS imagery for the Crazy Mountains Basin and uplifted margins, south-central Montana (22 November 1972, ID#'s 1122-17353-7, 17355-7; 23 November 1972, ID#'s 1123-17411-7, 17414-7).

Lineament Truth

The scale of ERTS imagery immediately suggests its use for analysis of faults or sets of smaller scale fractures, and this kind of application is virtually forced by the limitations of ERTS resolution. Most minor tectonic lines (less than 1-2 miles long) are not revealed in the imagery.

ERTS lineaments are a new form of geologic data. They exist independently of their interpretation in the same way that magnetic anomalies or hot springs exist regardless of how they may be understood. Interpretation of ERTS lineaments, like that of other forms of data, is usually a matter of establishing a relationship, not a specific or categorical identity, to other geologic features. Lineaments certainly have a variety of origins and at least a few of them are probably random alignments of otherwise unrelated features.

Many lineaments coincide with known faults and it seems likely that the vast majority of all our lineaments are directly related to faulting or jointing. Many of the conventional geologic criteria for recognition of faults correspond exactly to the criteria for recognition of lineaments. The obvious first step in interpretation of lineaments is to check their relationship to faulting.

Unfortunately, recognizing and mapping faults by conventional geologic techniques is at least as subjective a procedure as drawing lineaments on ERTS imagery - more so in many ways because most faults are located by a single geologist working alone on the problem. Individual geologists tend to have strong personal bias in their manner of interpreting evidence of faulting and vigorous disagreements between different workers are commonplace. Therefore, a conventional geologic map or field checking by conventional geologic methods can hardly be regarded as definitive techniques for relating lineaments to faults which tend to be obscure. Nevertheless, they are the best techniques available.

Map Comparisons. Very careful comparisons were made between ERTS lineaments (Figure 6) and compiled fault maps and field check information to produce a map showing lineament agreements with known faults (Figure 7). Results of the comparisons are given in Table I.

For Montana west of Longitude 110° W., an area of about 71,000 square miles, a comparison of Figures 6 and 7 at full scale reveals the following: Of some 1169 lineaments, 137 or 11.7% are coincident with faults shown on the state geologic map and regional tectonic maps, leaving 1030 or 88.1% in the uncertain category if more detailed and recent maps are not utilized for truth data. Surprisingly, 305 faults shown on the regional geologic maps were not seen as ERTS lineaments.

The above figures imply a surprisingly poor correlation between ERTS lineaments and mapped faults of short and intermediate lengths (except for overthrusts and thrusts, a large proportion of the major faults were seen as lineaments). However, more detailed data for expanded test sites within the larger area analyzed above indicate a better correspondence. For expanded test sites 354 A, B, C and 354 D (Figure 7), which have a combined area of nearly 27,000 square miles and 533 total lineaments, data indicate that 13.9 percent of the lineaments match faults shown on the regional maps and an additional 13.1 percent of the lineaments coincide with faults shown on more recent, detailed geologic maps covering most of the expanded sites. For these sites, 27.0 percent of the lineaments correspond to mapped faults.

The absence of ERTS lineaments for a significant number of faults shown on regional geologic maps is partly explained by the fact that 17 percent of them are thrusts or overthrusts having relatively low dips, which tend not to be expressed erosionally as straight lines of topography or drainage. Perhaps some of the other faults which are not matched by lineaments lack dips steep enough to develop straight erosional lines recognizeable as ERTS lineaments.

A detailed analysis was made for two smaller areas within expanded site 354 A, B, C. These were recognized as structural domains on the

Table 1. Comparison of ERTS lineaments with faults from regional maps and more detailed geologic maps of larger scale (see Figures 6 and 7).

	A Expanded Test Site 354 A,B,C. (23,000 sq. mi.)		B Expanded Test Site 354 D. (3600 sq. mi.)		C Western Montana excluding expanded sites (44,400 sq. mi.)	D All of Montana west of Long 110° W. (71,000 sq. mi.)
	# of lines (% of total)	mi. of lines (% of total)	# of lines (% of total)	mi. of lines (% of total)	# of lines (% of total)	# of lines (% of total)
Lineaments coincident with faults on regional geologic maps	50 (13.2%)	645 (20.8%)	24 (15.5%)	123 (15.3%)	63 (9.9%)	137 (11.7%)
Additional lineaments matched by faults on detailed geologic maps	54 (14.3%)	394 (12.7%)	14 (9.0%)	77 (9.6%)	- -	- -
Newly discovered and confirmed faults	2 (0.5%)	21 (0.7%)	- -	- -	- -	2 (0.2%)
Unevaluated lineaments (probably mainly controlled by fracture)	272 (72.0%)	2037 (65.8%)	117 (75.5%)	603 (75.1%)	573 (90.1%)	1030 (88.1%)
Total ERTS lineaments	378	3097	155	803	636	1169
Faults from regional geologic maps, not represented by ERTS lineaments	81	142	34	232	190	305

basis of coherent but different lineament patterns (see Fig 6 for colored and shaded domain locations in northwestern Montana). The areas were chosen because the quality of geologic mapping is generally very good and the difficulty of seeing either faults or lineaments very great. The quality of geologic exposures is generally poor throughout the areas, and the bedrock consists of extremely thick sections of uniformly resistant Precambrian strata in which displacements are rarely obvious. The areas provide a most demanding test of the reliability of ERTS lineaments as guides to faulting. Detailed geologic map truth shows that approximately 40 percent of the lineaments correspond with faults, fold axes, and other linear geologic features such as contacts. Approximately 32 percent were not directly shown on published geologic maps but could be added to them without doing violence to either the mapped outcrop pattern or the style of structural deformation. The balance of the lineaments, approximately 28 percent, are inconsistent with map truth because they fall in places where significant faults could not be added to the map without doing violence to the outcrop pattern and in some cases materially altering the apparent style of deformation. Our assessment of the comparison, based largely on general familiarity with the regional geology, is that the lineament map is closely similar to the regional pattern of faulting. A rose diagram analysis is reported in a later section.

Field Checks. Field checking of lineaments which did not match mapped faults was carried out for 12 lineaments at 17 localities, mostly within expanded test site 354 A,B,C. Localities yielding definitive results are shown by code numbers on Figure 7. Two new faults were confirmed at localities #1 and #2 along parts of lineaments having lengths of 7 and 14 miles, respectively. At localities #3, #4, #5, #6, and #9, evidence was found for fracture control in the form of joints and/or shears striking parallel to the trends of the lineaments, but no discrete faults could be located in the time

allocated for field checking. Basalt dikes occupy north-trending fractures at locality #9, which is in the Idaho batholith. At two other localities (localities #7 and #8) evidence for faults on trend with lineaments was found, but it was later learned that these faults had recently been mapped and are shown on a preliminary copy of U.S. Geological Survey 1:250,000 scale mapping. Along three other lineaments field checks were inconclusive. Evidence for faulting or fracture control along 9 of 12 lineaments investigated on the ground suggests strongly that a high percentage of the unevaluated lineaments on our map represent faults or sets of minor faults or joints. This is not surprising in light of the fact that we studiously avoided annotating other kinds of geologic lines such as folds and normal stratigraphic contacts.

Rose Diagram Comparisons. Another approach used in evaluating the relationship between ERTS lineaments and faulting was considerably more statistical. Rose diagrams of lineaments and faults for two domains in northwestern Montana were prepared and are shown in Figures 11 and 12, where they can be compared. Their resemblance is generally close although not precise. We conclude that the ERTS lineaments and faults in this region show essentially the same pattern and could be used interchangeably for statistical analysis of tectonic patterns.

We have no immediate explanation for the slight differences between the rose diagrams for ERTS lineaments and mapped faults in western Montana. We do not infer that they reflect adversely upon the significance of the lineament map or its overall utility for statistical analysis of fracture trends. A possible explanation is weak en echelon overlaps of faults to form lineaments aligned with the zone rather than individual faults. Or some of the faults may have been mapped in error.

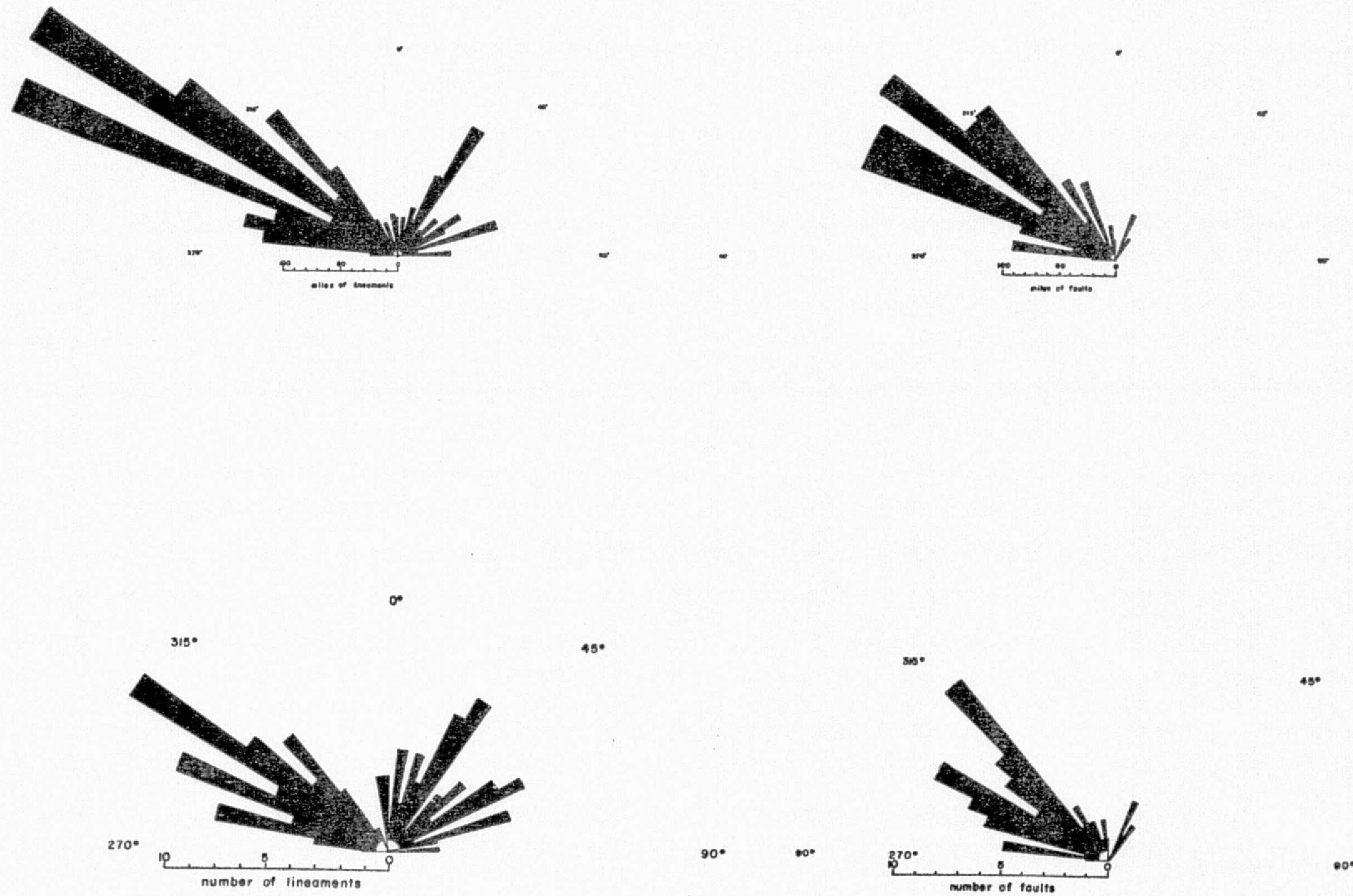


Figure 11. Rose diagrams for lineaments and faults in structural domain of Lewis and Clark lines northwest of Missoula. See Figure 6 for location of domain, shown in color. ERTS lineaments are graphed on left; mapped faults are graphed on right.

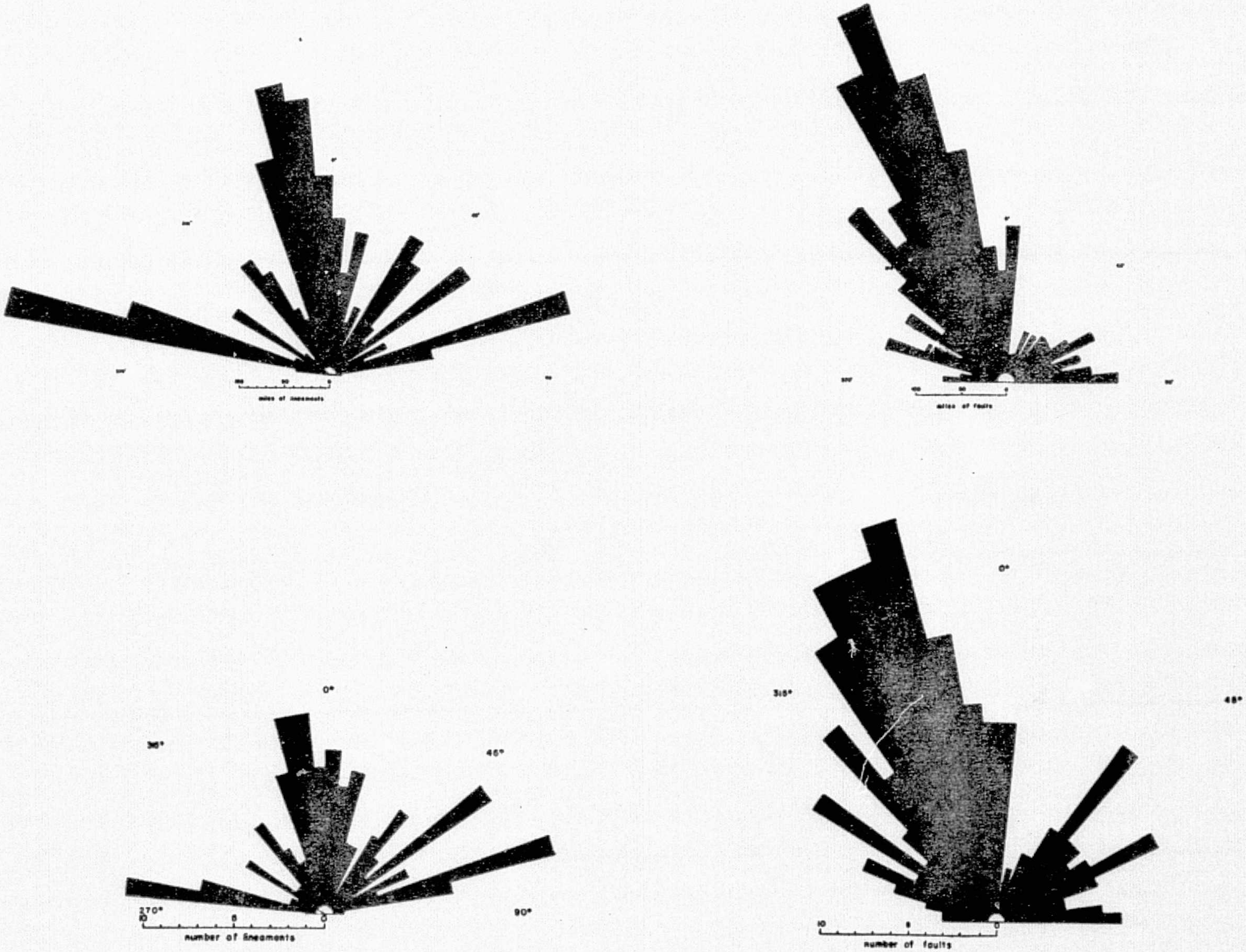


Figure 12. Rose diagrams for lineaments and faults in northwest Montana structural domain. See Figure 6 for domain location, shown by gray shading. ERTS lineaments are shown on left, mapped faults on right.

Crazy Mountains Basin Study. Detailed lineament annotation of the Crazy Mountains basin area of south-central Montana (Figure 10) was undertaken by the late William J. McMannis of Montana State University, a consultant to the project. His goals were to determine the utility of ERTS imagery for delineating the basin margins, folds, faults, and stratigraphically controlled lineaments, as well as to compare the pattern of fracture-controlled lineaments of the basin proper with that of its uplifted border areas. The area, which covers some 24,000 square miles, includes two major fault zones belonging to the Lewis and Clark lines (the Nye-Bowler and Lake Basin fault zones). Dip within the basin is mainly gentle (1 to 9°). Sparse vegetation and numerous outcrops enhance the utility of ERTS imagery for structural annotation and provide a useful contrast to most of the areas we studied farther west. The basin is underlain at the surface by Cretaceous and Paleocene sedimentary rocks. Its borders are composed of a variety of deformed sedimentary rocks as well as volcanics and igneous intrusives.

McMannis found he could effectively delineate the basin margins on the basis of topography, and folds and faults within the basin on the basis of standard photogeologic interpretation (nose patterns and offset strata or prominent linear escarpments). Outcrop trends of tilted strata were easily drawn and constitute about 13.5 percent of all annotations. However, recognition of sedimentary strata where horizontal was very difficult.

"Topographic linears", which make up 84.5 percent of all annotated lines, are equivalent to ERTS lineaments as used in this report. Because conditions in the area are ideal for their expression, they are shown on the map in much finer detail than is possible for most areas farther to the west. Some dikes in the radial swarm in the southern Crazy Mountains and some small igneous intrusives were also mapped.

The Lake Basin fault zone, with its short faults of northeast trend arranged en echelon in a west-northwest trending zone, could not

be located without the aid of ground truth information; the difficulty may be related to masking by other fracture-controlled lineaments of northeast trend. On the other hand, the rather similar Nye-Bowler line is boldly manifested on the ERTS imagery through obvious offsets of sedimentary beds and alignments of steeply-tilted strata.

Professor McMannis prepared a series of rose diagrams showing orientations of lineaments annotated within the Crazy Mountain basin and in the surrounding highlands. The most significant of these, Figure 13, indicate similar lineament distributions for both the basin and its margins, with a strong maximum oriented northeast. These suggest that no important tectonic differences exist between basin and margin. The cause of the northeast trend maximum is uncertain. Illumination from the southeast and control by Precambrian basement structures are possible factors.

Professor McMannis mapped a large number of structural features quickly and cheaply, but he points out that "nothing really new was seen in this study of the Crazy Mountains Basin and adjacent areas... a wide scope structural perspective then seems to be the main advantage." However, he also suggests that "the greatest use of ERTS imagery is likely to be in regional and worldwide reconnaissance geologic investigations. It provides a means of quickly ascertaining the location of major uplifts and basins, and perhaps of gaining a feel for the structural style exhibited. Sub-regional studies ... can benefit from the perspective of viewing large areas in one image ... areal geology seems most likely to be best done on the ground using conventional aerial photographs."

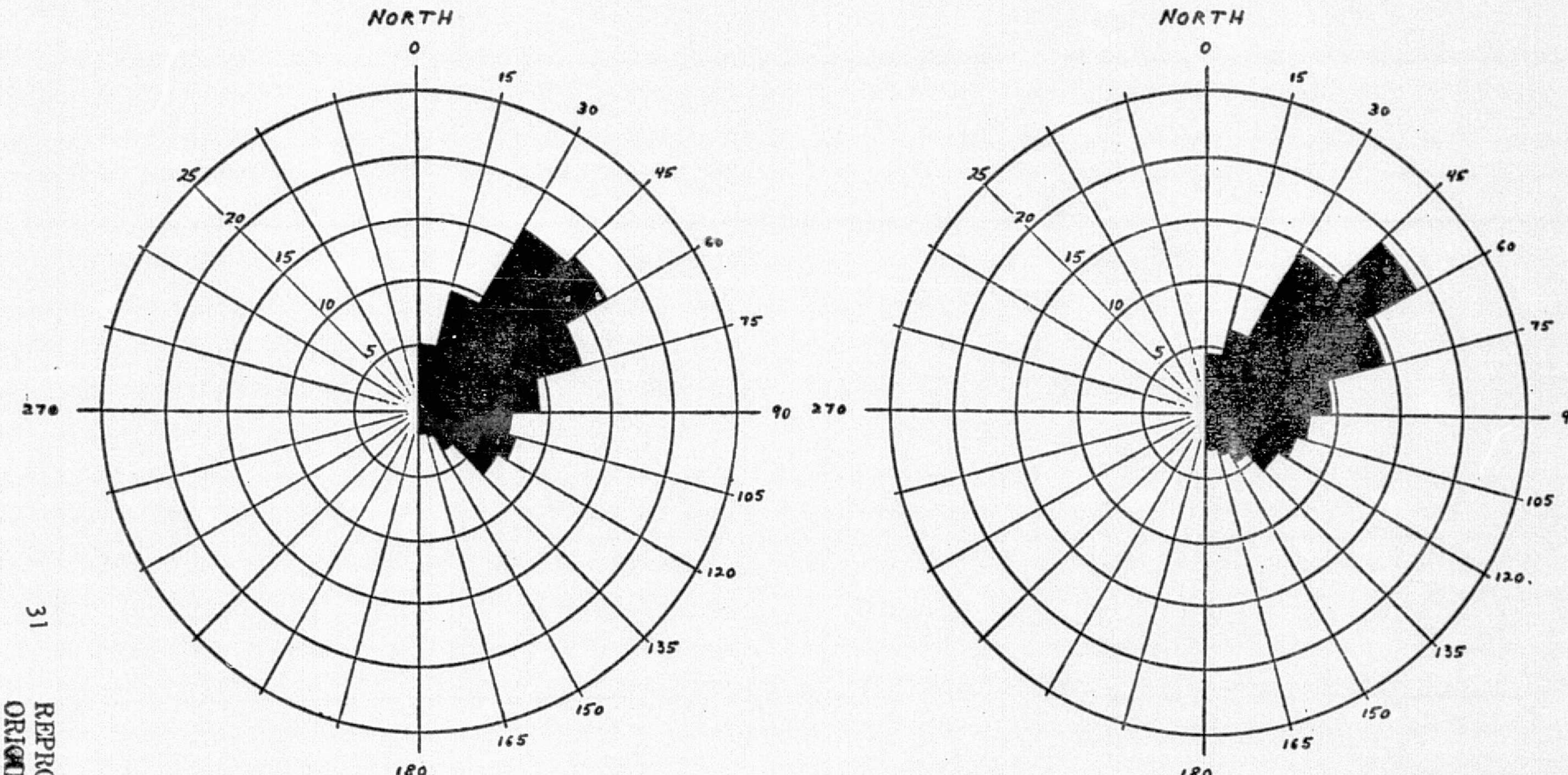


Figure 13. Rose diagrams for ERTS lineaments in Crazy Mountains Basin and its uplifted border areas (See Figure 10 for map data). Radius scale is in percent. Left diagram covers 1630 lines in uplifted areas marginal to the structural basin. Right diagram covers 1682 lines within the basin. Graphed lines include a small number of fold axial traces and linear outcrops, but are predominantly lines controlled by fracture.

Tectonic Meaning of ERTS Lineaments

Our lineament maps show most major high-angle faults, patterns of lesser fault and joint sets, and a good approximation of structural style. Field observations and rose diagrams for lineaments and faults indicate that a preponderance of lineaments not coincident with mapped faults are actually fracture-controlled and owe their alignment to the orientation of sets of joints or minor faults. The major shortcoming of ERTS lineament maps appears to be their failure to represent low-angle faults (thrusts and overthrusts), whose existence must be inferred from other data such as arcuate patterns. It is our observation that very useful lineament annotations may be made for heavily forested mountainous country underlain by Precambrian Belt strata which are homogeneous in their resistance to erosion and which practically never reveal folds or bedding attitude through landforms or tone. More detailed ERTS lineaments maps may be drawn for sparsely vegetated areas and for sedimentary terranes susceptible to differential erosion. Denser spacings of lineaments appears not only to be a function of drier, less heavily vegetated areas, but also of areas underlain by crystalline bedrock (gneisses and granites) of Precambrian and Cretaceous ages. A pattern of lineaments obtained in a few hours by annotating ERTS imagery can be used in much the same way as a geologic map of faults that might represent generations of field mapping.

Lewis and Clark Lines

A major feature in the tectonic framework of Montana is the zone of the Lewis and Clark lines (stippled in Figure 8) which extends southeasterly from northwestern Washington to the vicinity of Billings, Montana. It defines the northern boundary of the Columbia basalt plateau, the Idaho batholith and the Boulder batholith, as well as

the southern boundary of the Kaniksu batholith. We tentatively interpret it as an old and inactive continental transform fault. One of our major objectives was to determine whether such features could be advantageously studied in space imagery. Though it is often vague and discontinuous on geologic maps, we had held some hopes that through-going features in ERTS imagery, no matter how subtle, would delineate the major paths of this structural boundary. However, it has been annotated only as a swarm of parallel short lineaments along the zone of its passage through northern Idaho and into western Montana (colored band, Figure 6). The Lewis and Clark lines are manifest on our lineament map as a zone marking the boundary between regional domains of homogeneous lineament patterns. We interpret this as meaning that it functioned as a soft boundary between two parts of a continental plate that sheared through a broad zone rather than along a simple surface.

Apparently finding an inactive continental transform will involve more than looking for straight lines on ERTS imagery. Our experience suggests that one fruitful approach will consist of objectively defining domains of homogeneous ERTS lineament patterns and then examining the boundaries between them to determine whether they may also be plate boundaries. We have begun to apply this approach by dividing our region into arbitrary 50 mile squares. Lineaments within each square are being measured for azimuth and length and the results tabulated and plotted as rose diagrams. Homogeneous lineament domains can be identified by adding grid squares with similar rose diagrams until a change is found. We believe that such a procedure will be a more fruitful approach than looking for boundary lines on ERTS imagery and lineament maps, especially for areas east of Missoula.

Folds

For areas of sparse vegetation, mainly in the mountains and on the plains east of the Continental Divide, plunging folds with widths (wave lengths) larger than 3 miles (5 Km) may usually be delineated from ERTS imagery; the minimum wave length mapped was one mile (1.6 Km). Folds are recognized on the basis of looping parallel ridges or tone bands (Figures 3 and 4). In the case of large anticlinal uplifts such as the Little Belt and Big Snowy Mountains, which are some 8 to 30 miles across (14-48 Km), dip direction on the flanks can be determined from dip slopes and flatirons (Figure 14). For smaller folds identification of fold type (anticline or syncline) was possible from dip direction based on ridge asymmetry. About half of the 30 folds delineated in the Three Forks area and Test Sites 354D and F were correctly identified by type. Determination of dip direction from asymmetric ridges on the smaller folds is enhanced by stereoscopic viewing of sidelapping image pairs.

In Test Site 354D and 354F, ten plunging folds wider than two miles were mapped from U-2 photographs at a scale of 1:125,000. Of these, seven had been delineated previously using ERTS prints, and six of these had been properly identified as anticlines or synclines; the seventh was indeterminate. It should be noted that when plunge is not present, the mapping of small folds from ERTS imagery becomes virtually impossible because ridge and tone bands are aligned rather than looping.

Folds mapped from ERTS imagery were compared to the Geologic Map of Montana (Ross and others, 1955), and a significant discrepancy was turned up for a large anticlinal nose near Ringling (Figures 4 and 15) where the location of the axial trace could be drawn accurately from the ridge-valley and tone pattern. At the horizon of the Cretaceous Eagle Sandstone, which is expressed as a prominent hogback with dark-toned forest on the northerly side, the nose as shown on the state map

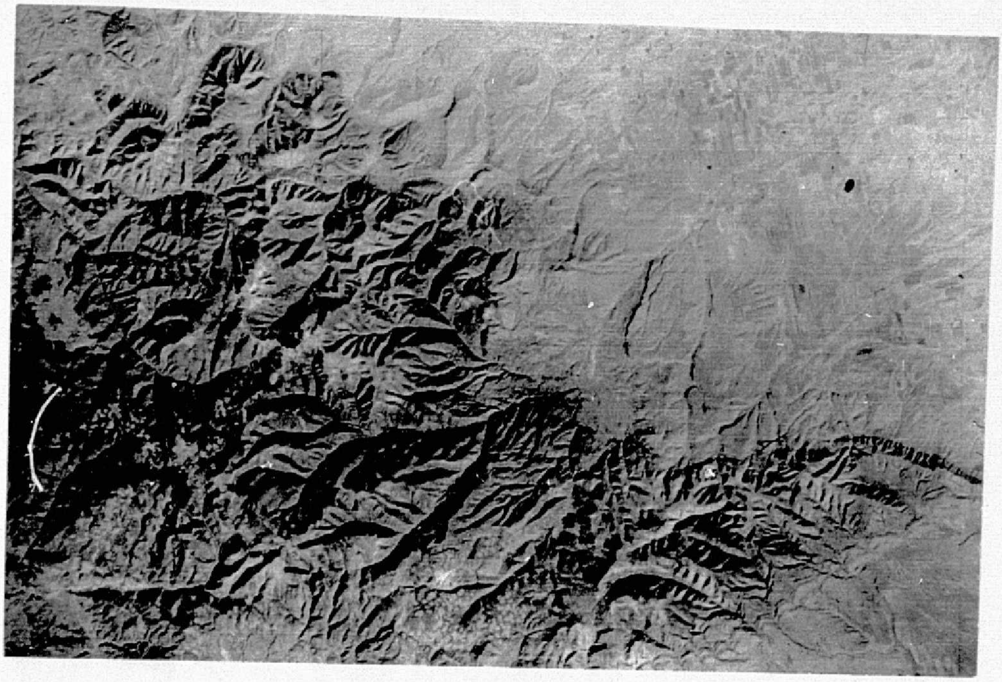
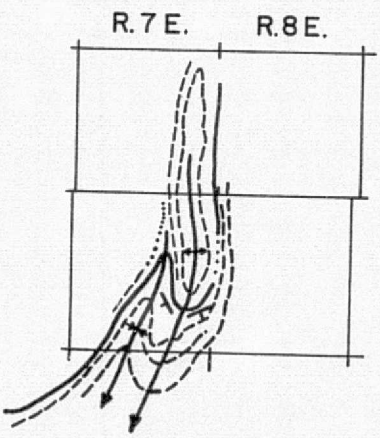


Figure 14. Expression of dip slopes and domes on Central Montana uplift, Little Belt Mountains. Note prominent southeast dip seen from shadowed flatirons in southeast corner. (ID# 1087-17402-6, 18 October 1972). Width of scene is 48 miles (77 km).



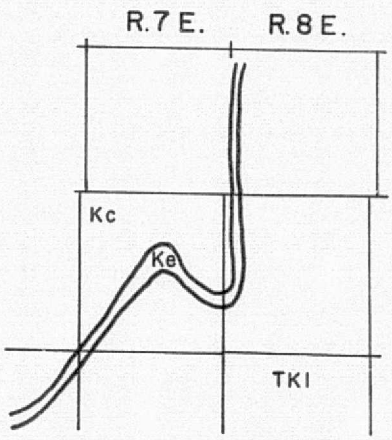


Figure 15-1 (left). Detailed ERTS delineation of noses near Ringling, Montana. Solid line represents base of Eagle Sandstone. (From 1:500,000 prints of Figures 3 and 4). Satellite mapping here reveals significant errors in Geologic Map of Montana, shown in Figure 15-2 (right). Kc - Colorado Shale, Ke - Eagle Sandstone, TKl - Livingston Formation.

is located 1.5 miles (2.4 Km) to the east of its accurately drawn ERTS location, and the trend suggested by the geologic map is some 20° off the clearly expressed ERTS trend. The data from ERTS here suggests significant errors of 0.5 to 1.5 miles in ground reconnaissance mapping which should be corrected when the state map is revised.

A number of large folds exist in the regions of western Montana underlain by Precambrian sedimentary rocks belonging to the Belt Supergroup. Except for the White River syncline, which is capped by lower Paleozoic limestone, none of these folds is revealed in the ERTS imagery. This is due in part to the heavy forest cover and in part to the monotonous lithologies of the Precambrian argillites, quartzites, and impure limestones, which are nearly uniform in resistance to erosion and therefore not expressed topographically.

Circular Structures

Although not included on the final lineament map, all circular and arcuate patterns were annotated during lineament mapping, and efforts were made to identify their origins. Search of the literature and the general regional familiarity of the investigators explained most of the circular structures as being related to known igneous intrusions.

Granite stocks at Castle Mountain near White Sulphur Springs and McCartney's Mountain northwest of Virginia City are conspicuously evident as circular structures. Numerous other circular or near-circular granite stocks such as those in the Flint Creek Range, the Belt Mountains, and the Marysville stock are subtly visible on imagery received from some orbital passes and not visible at all on others. Still other granite stocks, such as some of those in the Garnet and Sapphire Ranges, are not visible on any of the ERTS imagery.

Several fields of laccoliths and stocks comprising parts of the Montana alkalic igneous province appear on ERTS imagery as swarms of small circular structures. These are conspicuously evident in the Moccasin and Judith Mountains north of Lewistown (Figure 16), the north flank of the Little Belt Mountains (Figure 14), and in the Sweetgrass Hills east of Cutbank. Domes at the first two localities were annotated at a scale of 1:500,000 (Figure 17). They were recognized on the basis of topographic expression revealed by low sun angle illumination. Domal form exposed by differential erosion was easily seen, and in some cases concentric ridge-valley topography at the margins was also visible. These domes, which are the result of intrusion at horizons ranging from Cambrian to Cretaceous, range in diameter from less than 3 miles (5 Km) to 8 miles (13 Km).

Other laccoliths and stocks are visible, even though inconspicuous, in the Highwood, Crazy and Adel Mountain areas, all in west-central Montana. Eroded volcanic vents and radial dike swarms asso-

ciated with these intrusive bodies are not visible, except for a few short segments of some of the larger dikes, on the ERTS imagery (Figure 18). It would not be possible to deduce the nature of these smaller intrusive bodies from examination of ERTS imagery without the help of ground truth knowledge.

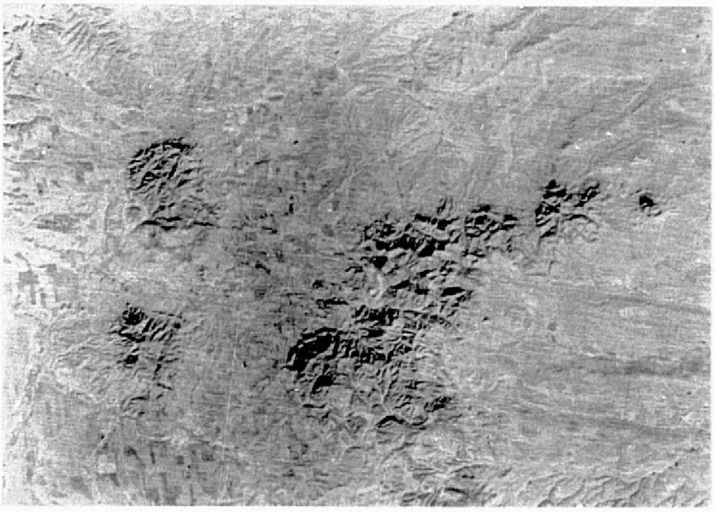


Figure 16. Prominent circular domes of intrusive igneous origin north of Lewistown. (ID# 1087-17402-6, 18 October 1972). Width of scene is 35 miles (56 km).

An ultramafic stock intrusive into Precambrian sedimentary rocks about five miles northeast of Libby in the northwestern corner of Montana is faintly visible on ERTS imagery as a circular target three miles in diameter (5 Km). Other, much smaller, ultramafic diatremes known to exist in the breaks of the Missouri River near Great Falls are not visible.

A number of small volcanic centers and one cluster of apparent maar craters, all probably Pleistocene or latest Tertiary in age, exist in western Montana along the line of the Lewis and Clark lineament system. None of these features are visible on ERTS imagery, no doubt largely because of their small size.

Several distinct circular patterns were noted on ERTS imagery

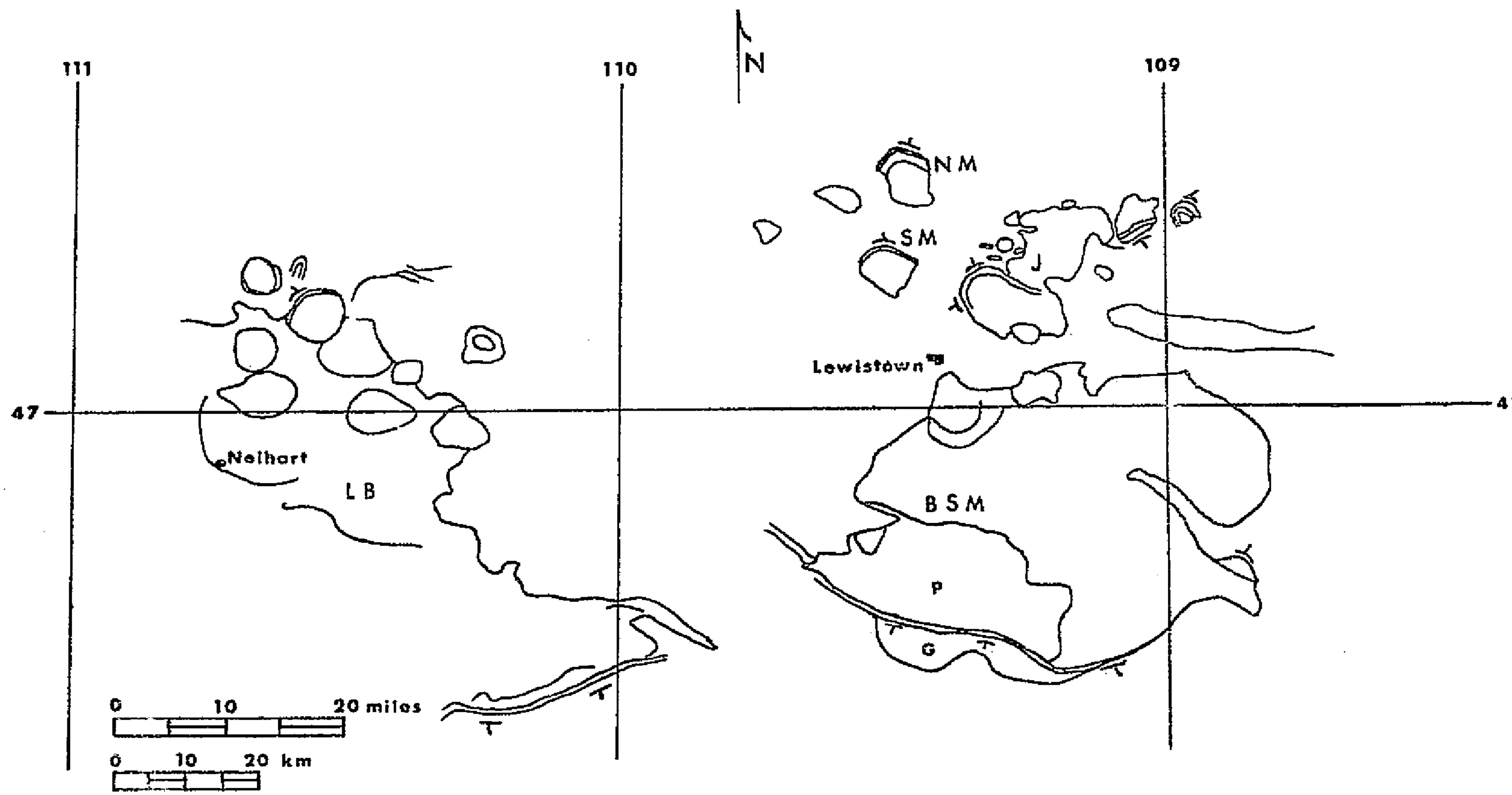


Figure 17. ERTS delineation of intrusive domes and the Central Montana uplift in the Neihart-Lewistown area (see Figures 14 and 16). J - Judith Mountains, NM - North Moccasin Mountains, SM - South Moccasin Mountains, BSM - Big Snowy Mountains, LB - Little Belt Mountains. Double and single lines around outside of Big Snowy and Little Belt Mountains represent approximate horizon of Jurassic Morrison Formation. P - Paleozoic strata, G - area of terrace gravels on state geologic map.

of the northeastern part of the Idaho batholith, all of them in remote and very rugged areas. No explanation for these was known to the investigators or available in the published literature. One of these structures, located in Idaho south of the Lochsa River (T.35N., R.13E.), is five miles (8 Km) across and is defined by arcuate canyons. It was visited briefly by three students, who found fine-grained igneous rocks that appear likely to be associated with volcanic activity. No evidence of shattering or shock metamorphism was noted.

Everyone involved in geologic annotation of the Montana ERTS imagery was alerted to the possibility that meteoritic impact structures might be found. It is easy to imagine a sizeable crater existing unknown somewhere in the heavily wooded and roadless areas of the northern Rocky Mountains. Except for the unexplained features in the Idaho batholith, no circular structures have been noted that can not be explained by igneous intrusion. It seems unlikely that we have discovered any meteorite impact structures unless the magma for one of the igneous-related circular features was generated by impact.

Identification and Mapping of Rock Units

Alluvium

Floodplain alluvium and alluvial deposits of low terraces along the larger streams are recognized from ERTS imagery on the basis of visible streams, meander patterns, slope breaks, and the presence of growing pasture grass, crops, brush and deciduous trees nourished by artificial irrigation or natural sub-irrigation. During the growing season, these areas are much darker in tone in Band 5 and much lighter in tone in Band 7 than than surrounding unwatered areas.

Partly dissected upland alluvial blankets of late Tertiary or Quaternary age in parts of eastern Montana are difficult to recognize. Their presence may be suggested by smooth image texture and dry farming patterns (fallow and vegetated strips) on the plains flanking mountain uplifts.

Glacial Deposits

The high plains north of the Missouri River were largely covered by continental ice during the Wisconsin glacial period, and presumably during earlier ones as well although very little is known about them in Montana. Continental glacial deposits are locally recognizeable on ERTS imagery of the high plains of Montana where they are densely dotted by kettle lakes or hummocky on a larger scale than usual. Evidence of glacially disordered drainage is also locally apparent. Glacial outwash deposits are very difficult to recognize unless they are pitted by kettle lakes in which case they are difficult to distinguish from morainal deposits.

The extent of continental and mountain Wisconsin glaciation was mapped as a seminar project by Stradley (1974) using 1:500,000 scale Band 7 prints for the area immediately east of the Rocky Mountain

front from Canada to the Missouri River (ID#'s 1036-17565-7 and 1071-17513-7). The procedure was to annotate all discernable lakes and ponds and locate morainal boundaries at the outer edge of terrain with high lake density. The mapping was done rapidly and with confidence, except in the south, where an ice marginal lake apparently subdued the topographic expression of the moraines, making them difficult or impossible to trace. Stradley's map compares favorably with the reconnaissance glacial map by Alden (1952). Contacts are usually closer than three miles of one another, and the confidence with which the morainal boundary was drawn from ERTS imagery in the north leads us to conclude that the discrepancies are as much the fault of the ground truth map as of the ERTS map.

Farther to the east, partial mapping of the extent of Wisconsin continental glaciation on the high plains of Montana would probably be possible through examination of ERTS imagery but we believe that most geologists would find the product of such mapping too incomplete and fragmentary to be satisfactory.

Valleys gouged by major alpine glaciers in the higher mountains of western Montana are easily recognizeable on ERTS imagery as are the larger moraines left by those glaciers (Figure 5). Minor alpine glaciation is manifest on ERTS imagery mostly through tarn lakes and ridges scalloped by small cirques; valley gouging and terminal moraines left by small glaciers are difficult to see. Outwash deposits are also very difficult to recognize. We believe that the extent of major alpine glaciation in the high mountains of Montana could be mapped rather well through examination of ERTS imagery. The extent of minor alpine glaciation could be mapped to a very reasonable first approximation. Relatively little is known about the glacial geology of the northern Rocky Mountains so it seems likely that mapping from ERTS imagery would produce a worthwhile contribution.

In parts of Test Sites 354 A-C and B, underflight color infrared photography was used successfully for detailed delineation of Pleisto-

cene surficial deposits in the lower Clark Fork and Flathead River drainages, where there are extensive deposits of till, outwash, and lacustrine deposits related to tongues of the Cordilleran Ice Sheet. The study was done as a cooperative pilot project by W. Mark Weber, who is familiar with the mapping units from a previous detailed ground study (Weber, 1972). He studied 1:125,000 scale RC-10 metric camera transparencies (NASA-ERAP Flight 72-125) under the zoom stereoscope and prepared a map at photo scale which demonstrated the feasibility of differentiating and mapping deposits of glacial, glaciolacustrine, lacustrine-outburst flood, and alluvial origins. Ground truth checks together with an examination of previously published maps have confirmed the photogeologic interpretations. In parts of the area, previously unrecognized deposits and stratigraphic relationships have been delineated by the photogeologic interpretation. Attempts to recognize the same units in ERTS imagery using black and white enlargements and color additive viewing were disappointing. The results suggest that stereoscopic color infrared satellite imagery with resolution between that of ERTS imagery and the underflight photography can be effectively used for glacial mapping in western Montana north of Missoula.

Several large ice-marginal lakes formerly existed on the high plains of Montana leaving shorelines and deposits easily recognizeable on the ground. These are not visible in the ERTS imagery. Neither is it possible to recognize evidence of the former existence of Glacial Lake Missoula, a very large lake formed by glacial impoundment of the Clark Fork River drainage in western Montana. But the channelled scablands of eastern Washington, an extensive tract scoured by the catastrophic floods released when Glacial Lake Missoula suddenly drained, are conspicuously evident.

Cenozoic Basin Fill

Intermontane basins in western Montana are filled to a depth of several thousand feet with unconsolidated sediments deposited during much of Tertiary time. Excavation by rivers flowing during Pleistocene time has dissected the Tertiary sediments, developing a complex topography of modest relief in the basin floors and depositing alluvium locally.

Approximate extent of Tertiary basin fill deposits is easily mapped from ERTS imagery because they coincide almost exactly with the floors of the basins, where there is a prominent break between forested slopes and open lowlands (Figures 1, 2, and 3). But success in mapping the extent of basin floors is not actually success in recognizing Tertiary basin-fill sediments from ERTS imagery. Several of the intermontane basins contain large areas of older bedrock exposed in the basin floor itself or in pediments marginal to the basin. Parts of the western end of the Missoula Valley and southern end of the Flint Creek Valley are floored by Precambrian and Paleozoic sedimentary rocks, and large areas of the Jefferson and Madison Valleys by crystalline basement rocks. We have not been able to differentiate these areas of older bedrock from areas underlain by Tertiary sediments by examination of ERTS imagery. The best conventional photogeologic approach to this problem is to base the distinction upon differences in drainage pattern and texture - areas underlain by older bedrock normally display a close texture and departures from dendritic pattern. Unfortunately, the erosional topography developed on valley floors is too low in relief and too small in scale to be easily visible on ERTS imagery.

Optical color enhancement using diapositives for two or three multispectral scanner bands in many combinations crisply differentiates basin floors from adjacent mountains. Sharp color differentiation of natural valley floor grasslands and irrigated farmlands is easily ob-

tainable, and the colored projections usually emphasize locations of vegetation-enhanced spring areas as well as gallery forests along streams. But we have not succeeded in finding optical color enhancer combinations that differentiate between valley fill and older bedrock in the valley floors.

Evidently the differences that make valley floors distinguishable from adjacent mountains on ERTS imagery are almost entirely based on vegetative cover rather than bedrock. The sagebrush and grass that covers most valley floors seems to have a spectral response quite different from that of the trees that cloak the mountain slopes. This conclusion is supported by the observation that in several places where forests extend onto the floors of intermontane basins, as in parts of the Flathead and North Fork Valleys of northwestern Montana, it is very difficult to find the boundary between valley floor and mountain slopes on the ERTS imagery.

Volcanics

We annotated ERTS imagery for three Cretaceous and early Tertiary volcanic fields in detail and made a cursory examination of the youthful Yellowstone Plateau volcanics to ascertain the recognition characteristics and mappability for volcanic rocks of different compositions, structure, age, and vegetative cover. Of the four fields, the Adel Mountain volcanics were easily recognized and accurately mapped. Two fields, the Lowland Creek volcanics and the heavily forested Yellowstone volcanics could be recognized and mapped with partial success. The fourth, the Elkhorn Mountains volcanics, could not be recognized in ERTS imagery. Our general approach was to study imagery until geologic boundaries of the volcanic fields became apparent, after which the boundaries were drawn on an overlay and checked against available ground truth information. For cases where the boundaries withstood the check against ground truth, the imagery was critically re-examined

to determine which characteristics were distinctive.

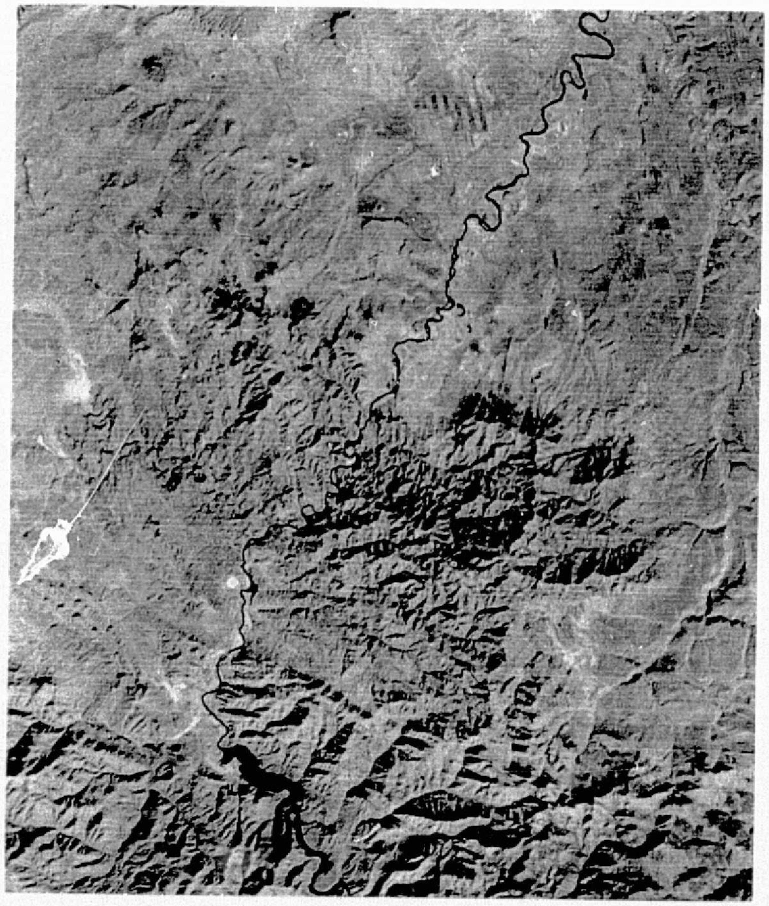
The Adel Mountain volcanic field, which lies on both sides of the Missouri River Canyon between Wolf Creek and Cascade (Figure 18) consists of some 3200 feet of dark-toned rocks ranging in composition from trachybasalt to latite and resting disconformably on shaly Cretaceous beds. Dips are gentle to moderate. Eruption probably occurred in latest Cretaceous time, when lava was also intruded outward as dikes to form a number of laccoliths to the northeast. The laccoliths have been unroofed and occur mainly as buttes exposing the igneous rock on the tops and upper edges.

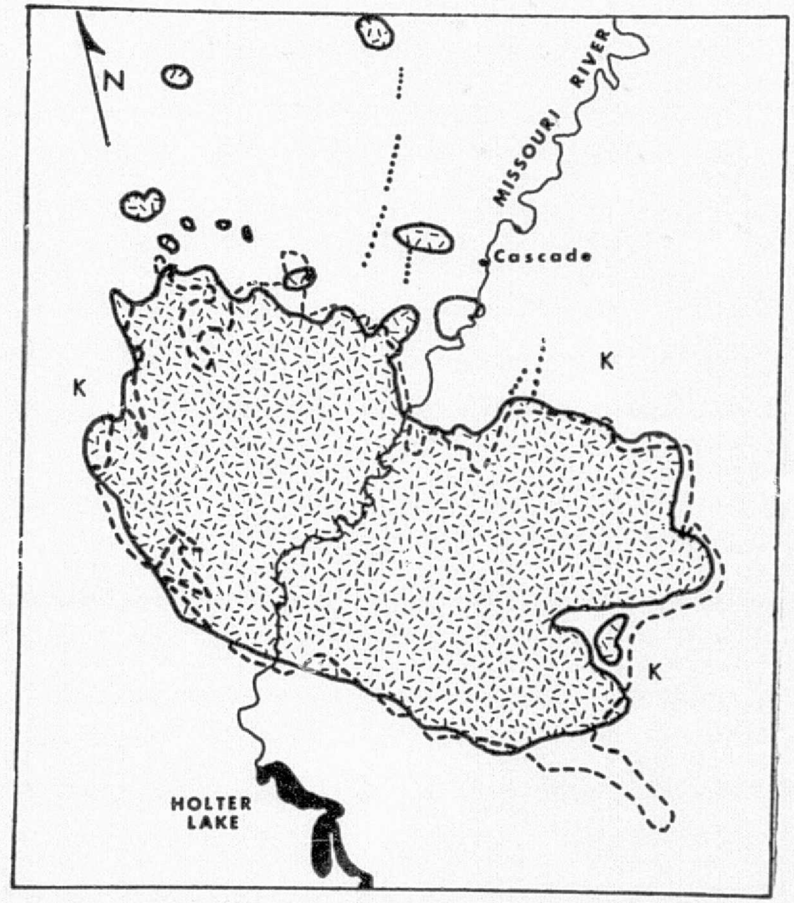
The Adel Mountain volcanic field and its outpost laccoliths are distinguished by dark tone; this tone, which results from a combination of bedrock influence and scrub forest cover, is apparent even where trees are absent. The main field is characterized also be rough topography and medium-textured drainage of irregular pattern, as well as lack of regular internal structure. The larger laccoliths show mesa-like form. Surrounding grass-covered Cretaceous strata are lighter in tone and smoother in image texture.

Comparison of the ERTS-drawn contacts of the volcanic field with those of the Geologic Map of Montana indicate excellent correspondence. Contacts are within a mile of each other over an estimated 80 percent of the perimeter. A minor peninsula of volcanics at the southeast corner of the field was not mapped from the imagery, and a mistake was made just south of Cascade, where patches of terrace were mapped as a laccolith (shown without pattern in Figure 18-2).

Four lines of northeast trend mapped from the imagery are the expression of thin, steeply-dipping dikes cutting horizontal strata. The two dikes east of the river are prominent ridges. Validity of ERTS mapping of the long dike on the west is complicated by proximity to a road.

Interpretation of the Lowland Creek volcanic field, located in the vicinity of Butte and Anaconda, is much more difficult than for the





0 10 miles 0 10 km

Figure 18-1 (left). ERTS-1 detail of Adel Mountain volcanic field and Missouri River Canyon. Buttes to north are unroofed laccoliths (ID# 1089-17515-7). Figure 18-2 (right). Contacts of Adel Mountain Volcanics drawn from Figure 18-1 (solid lines) compared with those of state geologic map (dashed). Dotted lines are dikes. K - Cretaceous sedimentary rocks. Pattern - volcanics.

Adel Mountain field. The Lowland Creek volcanics consist of some 6000 feet of flows and pyroclastics of quartz latite and rhyolite composition erupted during the Eocene, after erosion had exposed rocks of the Boulder batholith on which the volcanics lie. In general, these volcanics appear hummocky and are distinguishable by their relatively open drainage texture and lack of apparent structural control in drainage pattern (compared to the batholithic rocks). They are quite different in appearance from the younger Tertiary sediments with which they are in contact on the west; these are characterized by a smooth image texture. Parts of the boundaries between the volcanics and the granitic rocks and Tertiary sediments were successfully drawn from ERTS imagery.

Although it is beyond the outlines of our study area, we did receive imagery of northwestern Wyoming on which we were able to trace, fairly satisfactorily, the boundaries of the very young Yellowstone volcanic field and the outline of the Island Park caldera. These features, unlike the Adel Mountain volcanic field, are in heavily forested terrain and involve very light-colored volcanic rocks. Preservation of original flow and caldera landforms were important to this delineation.

The andesitic Elkhorn Mountains Volcanics located mainly on the east flank of the Boulder batholith were erupted during Cretaceous time, almost simultaneously with the emplacement of the batholith. Probably because they are close in composition to the batholithic rocks they presently appear indistinguishable in ERTS imagery.

From our experience viewing volcanic rocks in ERTS imagery it seems probable that young and undeformed volcanic fields are recognizable whether exposed in arid or forested regions. Older volcanic rocks which have been deformed or deeply eroded are very difficult to recognize regardless of their vegetative cover. Any volcanics which are mineralogically similar to the surrounding rocks will be difficult or impossible to distinguish. Recognition and successful mapping of the Adel Mountain volcanics was possible despite their age because they

are relatively undeformed, they contrast in tone and vegetative cover with the surrounding sedimentary rocks, their forest cover is sparse, and they have associated dikes and eroded laccoliths which are topographically expressed.

Granitic Rocks

Several major batholiths as well as numerous smaller intrusions of granitic rock exist within our study area and considerable effort was devoted to finding ways of recognizing them by examination of ERTS imagery. Although some limited success was obtained, we did not find generally applicable criteria for recognition of granitic rocks.

Ground observation of large areas underlain by granite in the northern Rocky Mountains shows that they usually display a very open drainage texture which is normally dendritic except where locally fracture-controlled. Hillslopes tend to be convex and smooth on a large scale although often dotted with large rounded outcrops. Forest cover is nearly continuous except for grassy openings on south-facing slopes and occasional meadows in higher mountains. These characteristics would seem to be sufficient to provide a basis for recognition of granite on ERTS imagery. Unfortunately, most of the country rock into which the granites of the northern Rocky Mountains were intruded happen to develop very similar topography and forest cover so recognition of granite in ERTS imagery turned out to be more difficult than had been expected.

Determined and systematic efforts to find a way to characterize granite by optical color enhancement met with very limited success. Imagery scenes including parts of the Idaho and Boulder batholiths were methodically run through the changes of color combinations and intensities to see if one could be found that would differentiate granite from other kinds of rock. Occasionally a combination would show a short stretch of contact between granite and its country rock but none were

found that would affect a large proportion of a batholith or two different batholiths in the same way. Variations in vegetation did show up very well under optical color enhancement, especially the brush-covered scars left by the enormous forest fires of 1910 in northern Idaho. Other forest fire scars were obvious in various color combinations, and we suspect that many of the unexplained color patches represented anomalies in forest vegetation caused originally by fire or insects. No systematic relationship between color patterns created in the optical color enhancer and distribution of granite were ever noted except very locally on such a limited scale that it seemed likely to be accidental. We concluded that color variations due to differences in vegetative cover for reasons unrelated to the bedrock geology overwhelmed any geologic effect.

Intrusive bodies are locally recognizeable on black and white prints for Bands 5 and 7, but their granitic composition is suggested only by geologic inference. Examples are McCartney's Mountain west of Twin Bridges and Castle Mountain near White Sulphur Springs, both of which are large granite stocks intrusive into Paleozoic and Mesozoic sedimentary rocks. They form isolated high mountains rising conspicuously above the surrounding countryside, and doming by intrusion is indicated by dip slopes on their flanks and by their circular patterns. However, nothing in the ERTS imagery directly identifies them as granite. Their composition must be inferred from their size and intrusive relationship.

Numerous granite stocks and small batholiths intrude Precambrian sedimentary rocks belonging to the Belt Supergroup. Some of the larger ones are subtly evident on ERTS imagery but others are not visible. Those that do appear are seen as faint circular or arcuate outlines enclosing an area of somewhat more open drainage texture and slightly different image texture. Both the Idaho and Boulder batholiths are largely surrounded by these same Precambrian sedimentary rocks from which they cannot be differentiated in ERTS imagery except locally.

The one notable success in recognizing granite on ERTS imagery came during examination of the Pioneer Range of southwestern Montana where large masses of granite are intrusive into Precambrian and Paleozoic sedimentary rocks. In this case, granite is characterized by a fine-textured, non-dendritic drainage pattern, which contrasts with a much more open dendritic pattern on Belt country rock and differentially eroded topography on layered Paleozoic country rock. Attempts to follow the granite contact on the imagery revealed substantial differences from the outline shown on the state geologic map (Figure 19). A field check extended by mapping on conventional aerial photographs showed the outline traced on ERTS imagery to be correct and the state map to be wrong. This added approximately 42 square miles (109 square Km) of granite to the amount previously mapped in the Pioneer Range. We believe it likely that further successes of this kind can be obtained using ERTS imagery in regions such as the northern Rocky Mountains to trace outlines of large intrusive bodies. However, ground or aerial photograph truth is required to establish the location of the contact at several sites before it can be traced on the ERTS imagery with any real confidence.

Both the Boulder and Idaho batholiths have contacts with volcanic rocks in several places. In the case of the Idaho batholith, these are the Challis volcanics and their equivalents, dominantly rhyolitic ashes erupted during Eocene time onto an erosion surface already developed on the granite. Parts of the Boulder batholith are roofed by the Elkhorn Mountains volcanics, an andesitic sequence approximately the same age as the batholith and apparently erupted from the molten granite as it intruded the crust. Other parts of the Boulder batholith are overlain unconformably by the Lowland Creek volcanics erupted during early Tertiary time. These volcanic sequences could not be reliably recognized on ERTS imagery or differentiated from the adjacent granites except very locally. Short sections of contact could be traced in places starting from points located on the basis of ground

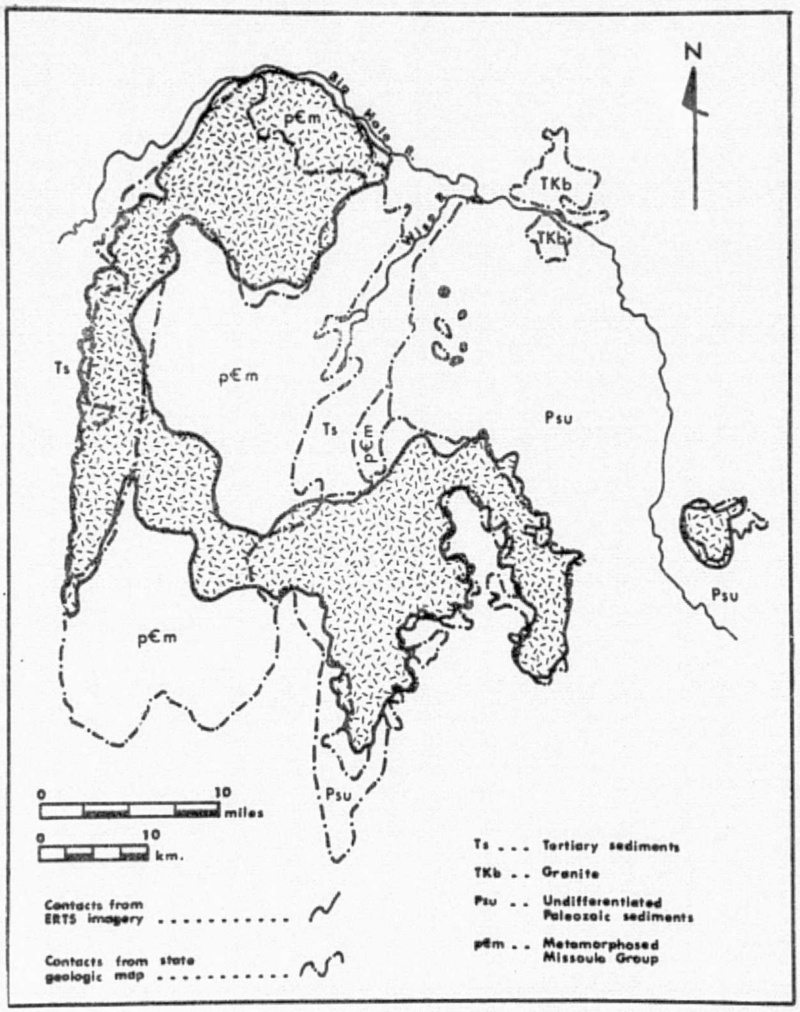


Figure 19. Granite contacts from ERTS imagery (solid lines) for Pioneer Range compared with state geologic map. Error in state map (west center) and delineation of 42 square miles of previously unmapped granite were confirmed by field check and study of conventional aerial photographs (ID# 1035-17520).

truth knowledge but it was not possible to outline these bodies by studying ERTS imagery. We doubt that investigators dealing with imagery of a similar geologic situation and comparable exposures elsewhere would be able to correctly deduce the geologic relationships or outline the outcrop areas of the major rock units without the benefit of ground truth control.

Drainage patterns on smaller granitic bodies appear to be essentially dendritic, insofar as can be judged by examination of the limited areas they cover, but those on the Idaho and Boulder batholith show strong evidence of structural control. Drainage in large areas of the Idaho batholith is dominated by streams following a very strong pattern of lineaments trending generally north and south - evidently the batholith is internally deformed. In some areas of the central and southern parts of the Boulder batholith the drainage tends to follow a curious pattern of intersecting arcuate and straight lineaments vaguely reminiscent on a large scale of the patterns familiar on suncracked mud. These different drainage patterns give the two batholiths distinctly different appearances in ERTS imagery and make it evident that simple recognition criteria for granites based on drainage patterns of ERTS resolution will not be generally applicable.

Further explanation for the difficulties encountered in developing definitive and widely applicable recognition criteria for granites derived from the fact that the Idaho and Boulder batholiths lie in distinctly different climatic regions and support different kinds of vegetative cover. The Idaho batholith is generally very well watered and supports a varied and luxuriant forest. Substantial areas at higher elevations were subjected to alpine glaciation. The Boulder batholith, on the other hand, is in a much drier region and supports a thin forest composed mostly of drought tolerant trees. Pleistocene glaciation was neither extensive nor erosionally effective except in a few drainages. Large areas of the Boulder batholith are nearly stripped of soil, probably by rainsplash erosion occurring when the

vegetative cover was greatly reduced during dry interglacial periods, and are now studded with large rounded outcrops. No such terrain exists on the Idaho batholith. These differences seem sufficient to account for the fact that the two large masses of granite display rather different ERTS image tones and textures and make it seem most unlikely that recognition criteria developed for one would serve to identify the other.

Several large and numerous small bodies of granite were intruded into crystalline rocks of the Precambrian basement in southwestern Montana during Cretaceous and early Tertiary time. These include the Tobacco Root batholith and the southern portion of the Boulder batholith as well as various smaller intrusions in the Beartooth Plateau and elsewhere. As might be expected, no difference was discernible in ERTS imagery between these younger granites and the chemically and mineralogically similar gneisses, schists and granites they intruded.

There is a critical level of image resolution somewhere between that of ERTS imagery and that of metric camera color infrared photographs from U-2 aircraft (NASA-ERAP Flights 72-125 and 74-140). Most granitic bodies east of the Idaho batholith may be recognized and mapped with some confidence in the aerial photographs. Examination of Forest Service high altitude black and white photography suggests that color is not a crucial factor. Major recognition criteria are scrub forest, drainage pattern and density, and visible effects of jointing.

Sedimentary Rocks

Recognition of sedimentary rock terrain in ERTS imagery is straightforward in all areas of Montana except the heavily forested mountains of the west. In Montana east of the continental Divide landforms of differential erosion, differences in image texture, and tone changes related to stratigraphically controlled vegetation patterns are the recognition characteristics of the Paleozoic, Mesozoic,

and early Tertiary strata exposed there. Easiest to delineate are upturned resistant units of limestone or sandstone expressed as linear ridges which reveal strike and sometimes the direction of dip (Figures 3, 4, 14). Individual ridges with lengths of 10-20 miles are not uncommon and easily mapped. With calibration from ground truth of aerial photographs, they may be stratigraphically identified. The most easily mapped stratigraphic marker is the dip slope at the top of the resistant Paleozoic section. Others include the Madison Limestone ridge, a valley representing Jurassic shales, and the resistant Cretaceous Eagle Sandstone.

In eastern Montana, where the Cretaceous and Tertiary sedimentary strata remain essentially horizontal in large regions, their outcrop areas are frequently distinguished by differences in vegetative tone or image texture. Two units which have characteristic expressions are the Eagle Sandstone, which is a bluff former, and the Bearpaw Shale, which is light-toned to locally whitish. Experimental annotation in the Porcupine Dome area (ID# 1085-17291) using prints of Bands 5 and 7 delineated 8 units which reasonably matched individual or combinations of individual geologic map units of Cretaceous and early Tertiary age. Attempts to trace the units laterally into imagery of the adjoining orbit proved unsuccessful because of tone changes along strike. The NASA-SCS ERTS mosaic for the area confirms the suggestion based on limited scene annotation that photogeologic mapping from ERTS may be done confidently for local areas, particularly on the flanks of broad uplifts, but is difficult or impossible without ground truth control in broad intervening areas. Nevertheless, a geologist unfamiliar with the region and without access to ground truth would be able to infer that it is underlain by very gently dipping sedimentary rocks which have been broadly folded and domed along the trend of the central Montana uplift (Little Belt Mountains, Big Snowy Mountains, and Porcupine Dome) and also along the Black Hills and Cedar Creek Anticline trends. Two-color enhancements of the mosaic for Band 5 and Band 7 emphasize the more subtle

tone differences seen on the black and white prints.

Large areas of central and southwestern Montana east of the continental divide are underlain by folded Paleozoic and Mesozoic sedimentary rocks. The upturned edges of resistant and non-resistant strata are conspicuously evident (Figures 3 and 4). It is possible to distinguish between Paleozoic and Mesozoic sedimentary rocks in parts of central and southwestern Montana because the Paleozoic section contains several thick limestone sequences and the Mesozoic sediments are predominantly clastic. The limestones, which are resistant in the prevailing dry climate, form bold ridges so sparsely cloaked in vegetation that the light tone of the bedrock is sometimes apparent in ERTS imagery. The most prominent of these ridges marks the Madison Group, which is some 1500 feet thick. The Mesozoic strata form grass-covered lowlands at the base of the Paleozoic dip slope. Sandstone ridges in the Mesozoic and Paleozoic are much less prominent than the ridges of Paleozoic limestone, and they tend to have a band of coniferous forest on their north facing slopes.

Most of Montana west of the continental divide is underlain by Precambrian sedimentary formations belonging to the Belt Supergroup exposed in a region that receives sufficient rainfall to support a moderately dense forest. All of the Precambrian sedimentary formations are very well indurated and none of them appears to be notable different from the others in its resistance to erosion. Neither are there conspicuous differences in the kinds of vegetation that grow on the various Precambrian sedimentary formations.

There is very little, if anything, in the ERTS imagery of western Montana that might reveal to a geologist unfamiliar with the region the fact that it is underlain by folded sedimentary rocks. Drainage tends to be dendritic, except where fracture controlled, and there are no linear ridges or tonal bands to betray the existence of sedimentary rocks or their structures. Although they clearly show features such as faulted range fronts, intermontane basins, drainage lineaments, and

glacial topography, ERTS images and even aerial photographs of the Belt terrain west of the continental divide border on being nondescript in terms of rock recognition. We believe that a geologist without access to local ground truth would be unable to make useful photolithologic inferences or recognize fold structures from ERTS imagery of this terrain.

Precambrian sedimentary formations in western Montana range from being almost unmetamorphosed in most of the region to high-grade metamorphic rocks along the northern boundary of the Idaho batholith. These large differences in metamorphic grade make no apparent difference in their appearance on ERTS imagery. Neither is it possible, as noted elsewhere in this report, to discern a clear difference in appearance between the Precambrian sedimentary rocks and granites of the Idaho batholith.

Mineral Resource Applications

Bentonite

The possibility of recognizing Bearpaw Shale known to contain bentonite beds of economic potential was investigated for an area on the flanks of the Ingomar anticline, where the ground truth is well known (Berg, 1970). The area is located about 80 miles northeast of Billings. Negative enlargement prints at 1:500,000 scale were made from diapositives of Bands 4, 5, 6, and 7 for a scene imaged on 16 October, 1972 (ID# 1085-17291). Band 5 was selected as best for annotation purposes. Two overlays were drawn, one delineating highly reflective areas of irregular pattern and the other showing a continuous tonal boundary thought to represent a lithologic contact. They were compared to a 1:500,000 scale lithologic map and to aerial photographs at a scale of 8" = 1 mile covering most of the bentonite deposits of the area. The overlays and ground truth data, which have been combined in Figure 20, indicate that the suspected photogeologic contact closely matches the sandstone-shale contact which marks the center of the anticlinal dome (Judith River - Bearpaw contact).

Known bentonite exposures in the area are too small to be recognized directly in ERTS imagery, but the irregular reflective patches may be a clue to their occurrence. These areas of high reflectivity are surficial clay pans (mud-filled channels and depressions) developed in this area on the Bearpaw Shale, where dips are less than 3 degrees and where bentonite beds are well exposed. This work suggests that target areas for Bearpaw bentonite exploration can be delineated rapidly from ERTS imagery of the Montana plains.

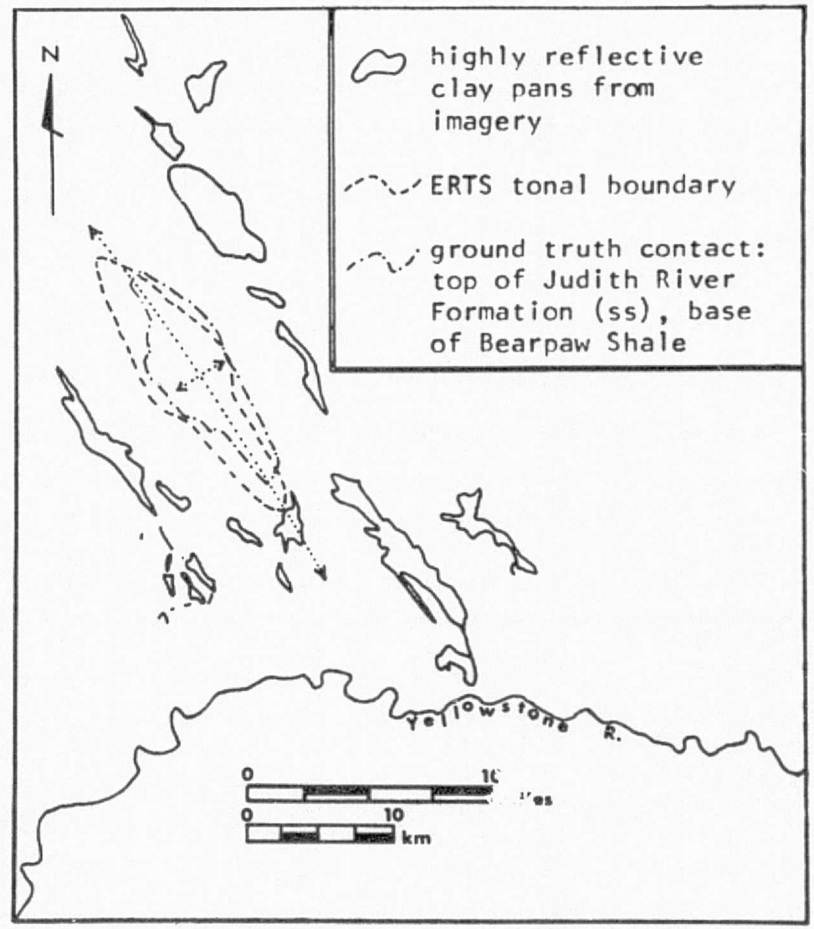


Figure 20-1 (left). Very light tone represents clay pans associated with low-dipping host strata of bentonite beds in Bearpaw Shale on flanks of Ingomar anticline northeast of Billings. (ID# 1085-17291, Band 5). Figure 20-2 (right). ERTS annotations compared with ground truth.

Possible Applications In Petroleum Geology

The use of ERTS lineaments to delineate paleotectonic hinge lines of interest to stratigraphers and petroleum geologists was investigated by George Shurr (1975) as part of a dissertation study of lower Montana Group marine cycles in eastern Montana and adjoining South Dakota. Prior to beginning field and subsurface stratigraphic studies and while participating in a seminar on satellite geology, Shurr examined ERTS imagery to look for indications of tectonic boundaries which might mark the edges of basement blocks. Using overlays and 1:1,000,000 scale prints for Band 5, he annotated all straight stream segments and straight boundaries of tone and texture producing a linear component map (Figure 21-1). On this he delineated zones or "packages" of line concentrations which he termed "lineaments".

These "lineaments" were refined by comparison with regional aeromagnetic maps and a geologic map, gaining two additional "lineaments" and making width changes in four others (Figure 21-2). Confidence in the ERTS delineation was reinforced by coincidence of the "lineaments" with magnetic features and geologic structures such as igneous domes, faults, folds, fold terminations, and strike change.

Shurr's regional stratigraphic studies indicate that lower Montana Group sedimentation was controlled by hinge lines located at certain of the "lineaments". He suggests that the "lineaments" mark the boundaries of basement blocks, where differential tectonism controlled sea floor topography and influenced the position of progradational shale prisms, as well as the distribution of bar and beach sands. These relationships suggest that ERTS mapping may be a useful tool in stratigraphic correlation and mapping studies related to petroleum occurrences.

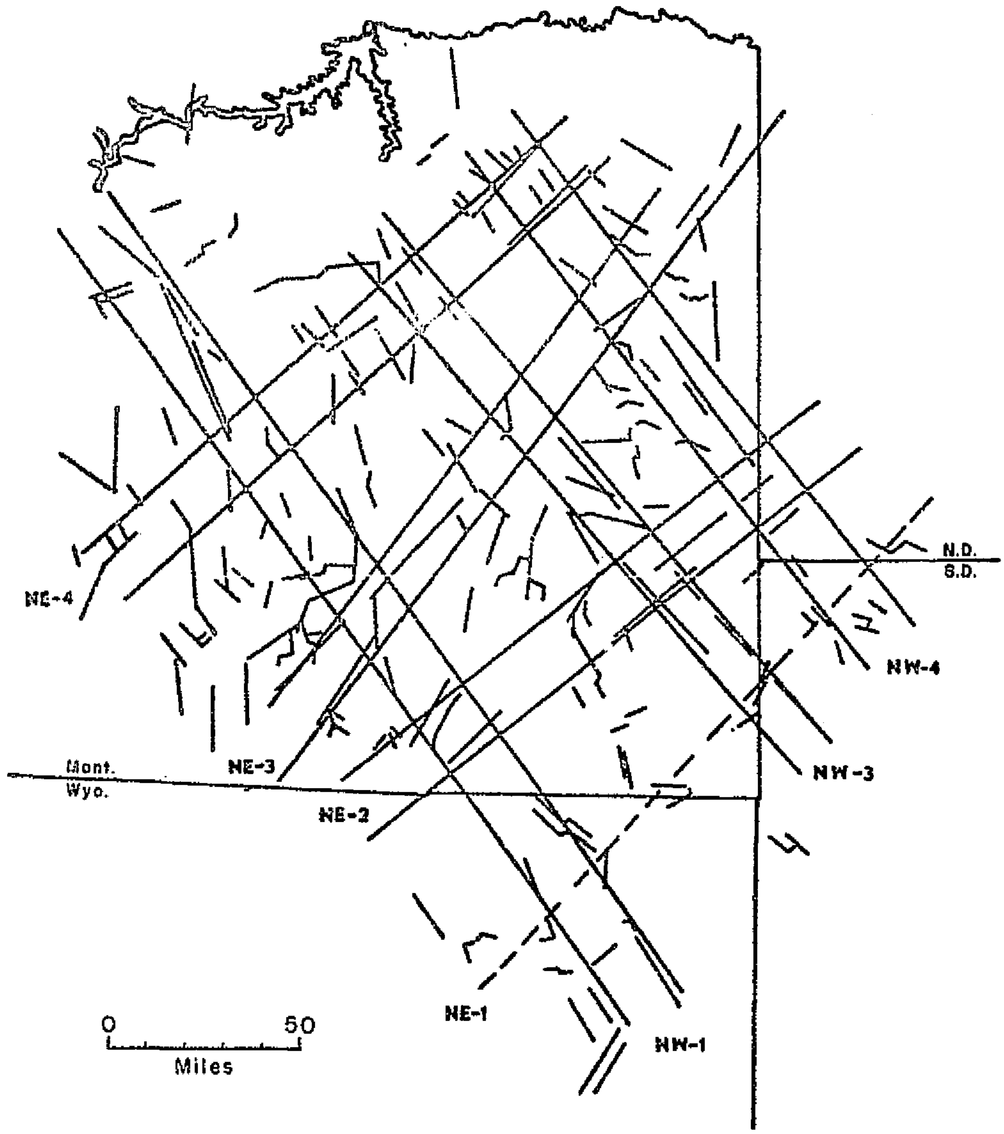


Figure 21-1. Linear components (shorter lines) and preliminary definition of "lineaments" (long lines) north and west of the Black Hills. "Lineaments" are zones marking trends or concentrations of linear components (after Shurr, 1975). Linear components were drawn from Band 5 prints for September-October, 1972 (ID#'s 1047-17170, -17173, -17175; 1084-17230, 17233; 1085-17285, 17291).

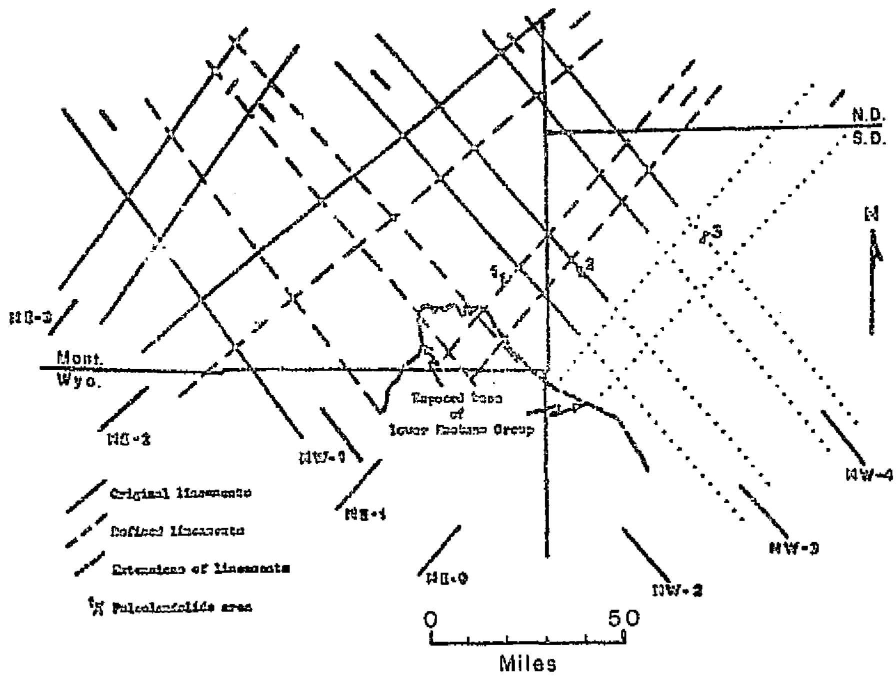
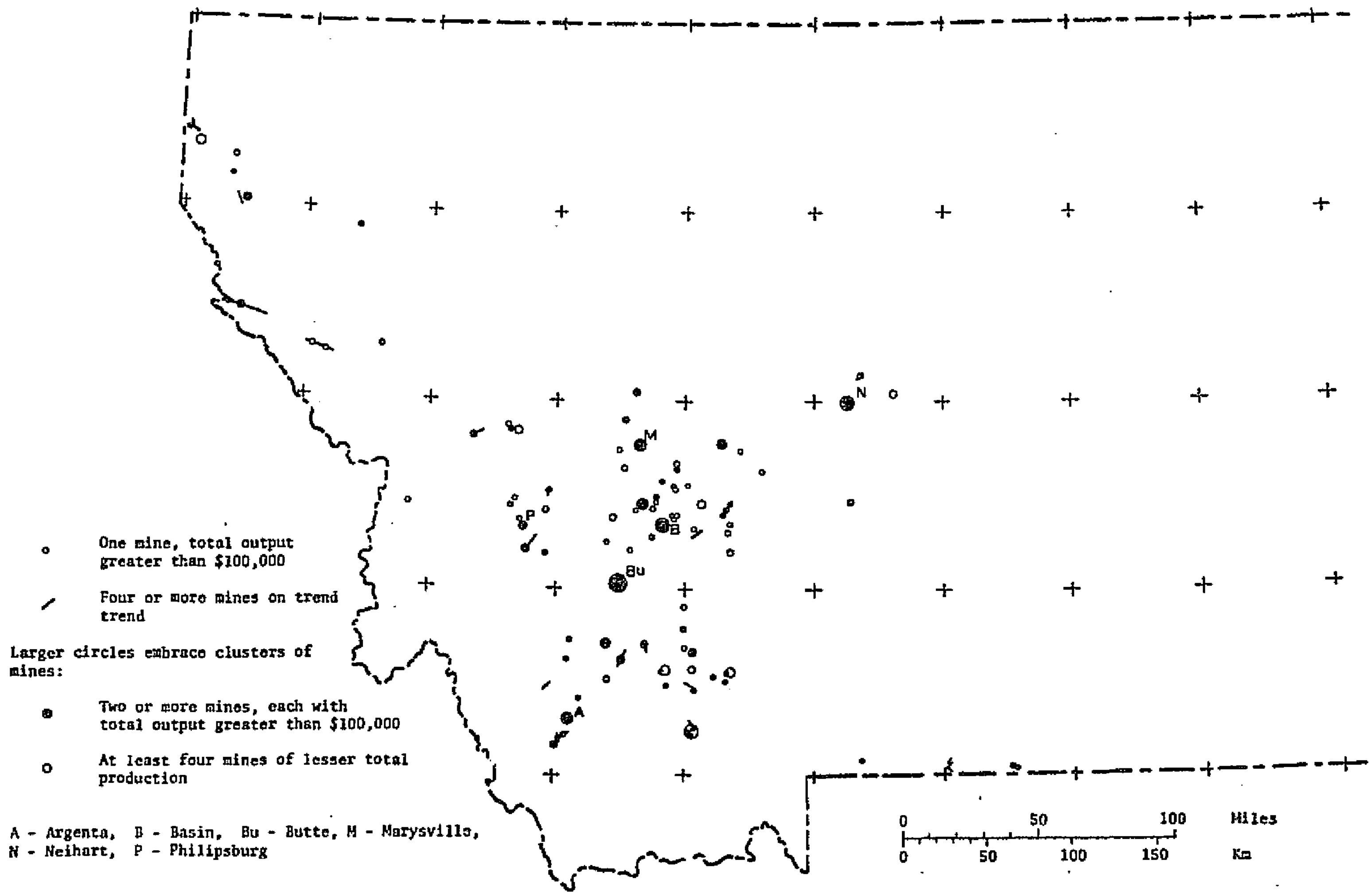


Figure 21-2. Refined "lineaments" derived from Figure 21-1 using aeromagnetic and geologic map data. "Lineaments" mark inferred boundaries of basement blocks whose paleotectonic movements generated hinge lines which influenced sedimentation in the lower Montana Group (after Shurr, 1975).

Hydrothermal Ore Deposits

Centers of hydrothermal mineralization were located by plotting mines and mining districts on the ERTS lineament map to determine any relationships of ore centers to lineaments, lineament density, lineament intersections, and lineament trends. Inspection of the map did not suggest any striking relationships, nor did analysis of a generalized map of hydrothermal centers (Figure 22 compared with Figure 5). Assuming that each location of one of the four categories of symbols for ore deposits and trends represents a center of significant hydrothermal mineralization, comparison with the lineament map reveals the following: Of 111 centers, 43% are on lineaments or just beyond their ends, and 48% are in areas of high lineament density. Although



Centers of hydrothermal mineralization in western Montana (generalized from 1:500,000 scale original prepared by Montana Bureau of Mines and Geology; data from U.S. Geological Survey Missouri Basin Studies No. 16).

Figure 22. Centers of hydrothermal ore mineralization in western Montana. Largest circles circumscribe many mines and indicate greater magnitudes of mineralization and production than small circles. See film transparency of this figure in pocket.

it is true that by far the greatest production has come from an area of high lineament density (Butte-Basin-Helena area), another major district (Philipsburg) is not characterized by high density. Nor are other areas of high lineament density correlated with significant occurrence of hydrothermal centers. High lineament density occurs mainly in areas of large batholiths and Precambrian crystalline basement rock. Lineament intersections appear to correlate with the locations of only 11 hydrothermal centers.

There are several instances of a linear trend of ore deposits coinciding with an ERTS lineament, but there is as yet no apparent way of discriminating between a mineralized lineament trend and the numerous others that show no sign of being mineralized. There are also linear trends of ore deposits that do not coincide with any mapped lineament. Many of the mining districts contain clusters of ore bodies that do not coincide with any mapped lineament. Many of the mining districts contain clusters of ore bodies that do not conform to any linear trend and do not appear to be related either to lineaments or intersections of lineaments. Only in the zone of the Lewis and Clark lines is there convincing indication of a systematic relationship between lineament trends and locations of ore bodies. Parallelism of symbol alignments with trends of coincident or nearby lineaments was noticed for only 11 symbols, of which 6 were in the domain of the Lewis and Clark lines west of Missoula. This zone is a major tectonic element that can be traced for several hundred miles and quite possibly corresponds to a plate boundary active during Cretaceous time. Mineralization along faults belonging to this zone has been well known in the Couer d'Alene district of northern Idaho and its extensions into western Montana for many years. Alignment of ore bodies along the trend of ERTS lineaments thus confirms a familiar geologic relationship. However, there are numerous lineaments within this zone only a few of which appear to correspond with trends of ore mineralization. There is nothing in the lineament map to indicate

which lineaments should be mineralized and which not.

In many areas of the northern Rocky Mountains, the lack of correlation between lineaments and ore deposition is readily understandable through consideration of the regional geologic patterns. In at least part of the region, it would be most surprising if there were any systematic relation between lineament trends and ore mineralization. A few of the recently discovered ore bodies are stratabound copper deposits within formations of the Precambrian Belt Supergroup. Most available knowledge about these deposits indicates that the ore minerals were deposited along with their enclosing sediments, and were not emplaced in the rocks at some later time as secondary mineralization. If so, their locations are more likely related to environments of sedimentation than to later fractures expressed as lineaments.

Economic ore deposits occur in a much wider range of geologic settings in the areas of Montana east of the continental divide. Some of them are associated with the contacts of small igneous intrusions emplaced late in the geologic history of the region. These intrusions are not aligned along lineament trends. A number of other mining districts are associated with centers of late volcanic activity, which also bear no obvious relationship to lineament trends, possibly because the blankets of volcanic rock obscure any such trends that might otherwise be visible in the underlying bedrock.

Efforts were made to relate tonal variations visible in the ERTS imagery to areas of known ore mineralizatin hoping that hydrothermal alteration of the bedrock or weathering of sulfide ore bodies might produce distinctive tonal patterns. None were observed that could be distinguished by visual examination from the much stronger tonal variations caused by geologically extraneous factors such as patterns of grazing, farming or forestry practices. It seems likely that vegetative cover is too dense throughout most of the northern Rocky Mountain region to make visual recognition of hydrothermally altered bedrock feasible.

Landform Recognition and Classification

Our geologic study and annotation of ERTS imagery has relied mainly on recognizing and interpreting landforms as revealed by topographic shadowing, vegetation difference, and stream patterns. Efforts have been directed primarily toward using ERTS imagery as a vehicle for study of various aspects of bedrock geology as they are expressed in the landscape, and not toward study of the landscape itself. Nevertheless, we have, from necessity, devoted considerable attention to landforms and it seems appropriate to include some comments on our observations in this report.

Elements of landscape observable in ERTS imagery include drainage pattern and density, free water surfaces, and ridges, hills, and valleys with relief greater than a few hundred feet. Smaller ridges are visible if they are favorably oriented to the illumination direction or have vegetation contrasts on opposite sides. Late fall imagery with low-angle illumination (approximately 20-30°) is far more useful than that spring and summer imagery (40-60°), which appears relatively flat and featureless in comparison. Recognition of topographic detail, especially where there is uncertainty related to tone differences, is sometimes considerably enhanced by stereoscopic viewing in sidelap areas for adjacent orbits (approximately 40% sidelap for our latitude). We found a pocket stereoscope and 1:1,000,000 scale prints to be convenient and effective for this purpose. Getting seasonal, cloud-free sidelap pairs was often a problem for this kind of study. Stereoscopic viewing revealed ridge assymetry and dip direction in some cases where it could not be determined from single print enlargements at 1:500,000 scale.

In the mountainous region of western Montana, topographic features which may be commonly discerned on ERTS imagery include river flood plains, cirques, glaciated valleys and their terminal moraines, parallel stratigraphically controlled ridges and valleys, mountain

fronts at the edges of the high plains, scarps, and Cenozoic basins. Cirques, recognized by the presence of tarns and by their form, are most easily identified where forest cover is absent.

Topographic boundaries between mountain ranges and intermontane basins or the high plains are generally obvious on ERTS imagery but do not always coincide with the structural boundaries. Where older range marginal faults are crossed by pediments, the structural boundary is generally invisible or very subtly revealed by slight changes in drainage density. If, as is often the case, the pediment is a Pleistocene landform cut on Tertiary basin-fill deposits, the structural boundary between mountain and intermontane basin is completely invisible on ERTS imagery and only the topographic boundary is visible.

Drainage patterns are generally easily visible in mountain blocks and it is possible to determine by inspection whether they are dendritic or in some way structurally controlled. Bedrock structure is most often revealed on ERTS imagery by departures from the normal dendritic pattern of drainage networks. It is usually possible to infer the kind of structural control of non-dendritic drainage patterns visible in ERTS imagery by conventional photogeologic methods.

Variations in drainage density are also easy to recognize in ERTS imagery of mountainous areas, these usually relate to variations in kinds of bedrock but are also affected by such variable as slope aspect and quality of vegetative cover. Open drainage textures tend to develop in areas underlain by permeable bedrock and soil; close drainage textures on surfaces less able to imbibe water. It is usually safe to infer that adjacent large areas having different drainage textures are underlain by contrasting kinds of bedrock and such variations have locally proved to be useful guides to the identity of the bedrock. In northwestern Montana, a region underlain almost entirely by Precambrian sedimentary formations belonging to the Belt Supergroup, outcrop areas of the Wallace Formation generally exhibit much closer drainage textures than those developed on other

stratigraphic units. Unfortunately, the variations are not sharp enough to permit precise delineation of the rock unit boundaries or recognition of smaller outcrop areas - those less than several square miles in extent.

In the plains areas of central and eastern Montana commonly recognized landforms include river floodplains, the dissected areas of river breaks, smooth upland surfaces, low, sinuous scarps localized at horizons of horizontal caprock, broad, elongate upwarps, laccolithic domes, and looping ridges and valleys expressing eroded folds. Under favorable conditions dip slopes and flatirons may be discerned on the flanks of the uplifts, domes, and folds. Criteria other than topographic which aid in recognition of these features are irrigated fields on floodplain-low terrace areas, grain fields on upland surfaces, and brush or forest in the river breaks and on the uplifts.

Drainage systems develop much less relief on the high plains and in the intermontane basins than in mountainous areas, so their patterns and textures are correspondingly more difficult to see in ERTS imagery. Nevertheless, they are visible in many places and appear to be useful as guides to the kind and structure of underlying bedrock. Much of the high plains surface, for example, is underlain by a thick bed of coarse gravel sufficiently permeable to enforce development of a conspicuously open drainage texture. In areas where the gravel is lacking, much closer drainage textures develop - in some areas badland topographies. Many of the streams on the high plains, and a few of those in the intermontana basins, follow very straight courses that appear to be fault controlled.

Estimation of relief from ERTS imagery can be done in a very qualitative way utilizing vegetation and early or late snow for high elevation areas and shadowing for low, steep slopes. Estimation of slope gradient for smooth slopes may be done more quantitatively where they face away from the sun and their slopes are in the range of the sun angle at some season of the year. The method requires

consecutive ERTS passes for determination of the grazing angle of illumination. Another method for estimating slope is use of the standard angle of repose for local places where large talus slopes are visible. Although the above methods might be applied to pioneer studies in unmapped areas elsewhere in the world, they are either too vague or too limited in opportunities to be practical in landform analyses where topographic maps or aerial photographs are available.

Educational Impact

Educational programs in geology at the University of Montana have benefited greatly from the presence of the ERTS project in the department. Beyond the short term benefits of research support for graduate students and faculty, there are less obvious long-term benefits which will probably prove to be far more important when they have finally exerted their full impact.

By long tradition, educational programs in geology have proceeded towards increasing specialization and attention to detail. As students proceed higher in the curriculum, they tend to narrow their intellectual focus, often to the point of overlooking whatever broader significance their interests may have. The ERTS program has been a powerful and stimulating antidote to that nearly universal trend and has had the effect of leading many of our students to take a much broader and more comprehensive view of geology than they would otherwise have done. This change in view and perspective is especially appropriate at a time when much of the major research in geology is directed towards large-scale tectonic interpretation.

Space imagery has a compelling quality of perspective and immediacy not possessed by any other kind of data. Maps at the same scale seem abstract and separated somehow from reality; they are not convincing. Ground views and ordinary aerial photographs are convincing but lack perspective; people limited to that kind of data tend to develop an ant-in-the-grass point of view. ERTS imagery immediately

conveys a sense of perspective and reality that otherwise requires many years of experience to develop.

Displays of ERTS imagery on the walls of the Geology Department have stimulated interest in regional geology and tectonic interpretation at all levels. A giant mosaic of the United States is used as an exciting focus for discussion sessions in our large introductory course. Use of imagery in advanced courses and seminars has been equally effective and has led faculty and students into very broad considerations of geologic relationships. Features that had always been considered as separate and distinct problems are now seen to be related and are mentioned in the same sentence rather than in separate courses. We believe that this change in view and added perspective will have a permanent effect on our department that could not have been achieved in any other way.

Summary of Results

Print Scale, Seasons, Vegetative Cover, Spectral Bands, and Color Enhancement

We found 1:500,000 scale paper print enlargements ideal for most of our photogeologic and lineament studies. They provide needed space for annotation without significant sacrifice in image quality compared with 1:1,000,000 scale prints. Late fall imagery (sun elevation 20-30°) was significantly better for our purposes than spring or late summer imagery (sun elevation 40-60°) because of topographic shadow enhancement. Cloud cover during the spring and early summer prevented a thorough evaluation of vegetative enhancement of rock units during the time of greening and drying in areas of grassland or sagebrush, but we did observe examples of such enhancement for folded sedimentary rocks. Imagery for semi-arid and sparsely vegetated areas east of the continental divide yields more geologic information than for moister areas to the west, which are

heavily covered with coniferous forest.

Infrared imagery of Band 7 was used for most of our annotations because it minimizes the dark tone of coniferous forests, revealing topographic detail not seen in Bands 4 and 5. Band 5 imagery (red band) was used as a supplement to Band 7 where the differences in vegetation provided geologic information. Optical color enhancement was utilized in an extensive series of experiments aimed at rock recognition and contact delineation of major rock bodies. Although enhancements sometimes emphasized differences seen in black and white prints for the different spectral bands for sparsely vegetated areas east of the continental divide, the use of color did not significantly assist us in photogeologic studies. For heavily forested areas color enhancement for geologic purposes appears to be an impractical approach.

We found topography enhanced by shadow modelling to be by far the most useful photogeologic recognition characteristic, not only for lineament mapping but also for rock identification and delineation experiments. Image texture and drainage pattern were commonly helpful. Except for areas east of the continental divide and for valley alluvium and basin fill in the west, tone was a relatively unimportant recognition characteristic.

Lineament Mapping

Lineaments, a term here applied to straight geologic lines controlled mainly by fractures (faults or sets of joints) and expressed as scarps, segments of canyons or streams, and tone discontinuities, are the most abundant and easily mapped geologic features seen in the ERTS imagery of our area. We annotated lineaments ranging in length from 2 miles to 90 miles on overlays and compiled a composite map representing 21 ERTS scenes. Comparisons of annotations by five different operators indicates good precision and very little error in identifying lineaments, although some operators tend to be more conservative than others. Our map contains an apparent illumination bias favoring lines of north-

east trend over those trending in a northwest direction.

Lineaments were checked for all of Montana west of the 110th meridian against faults shown on the state geologic map and regional tectonic maps; the area of interest covers some 71,000 square miles. For two expanded test sites covering a total area of 27,000 square miles, we compared lineaments with faults shown on more recent, detailed geologic maps. Two smaller areas in northwestern Montana which represent domains of different lineament patterns were also evaluated by map comparison and rose diagram analysis. In addition, a large area in south-central Montana was annotated to compare lineament trend distribution within the Crazy Mountains Basin and in its structurally uplifted borders. The last mentioned project demonstrated that a much more detailed lineament map is possible for the sparsely vegetated and mainly non-forested plains area than for the heavily forested mountains west of the continental divide. Field checks were made along parts of 12 lineaments which did not correspond to previously known faults.

Our studies indicate that 12-15 percent of the ERTS lineaments coincide with faults shown on small-scale regional maps, but that when detailed maps are also used the proportion of lineaments corresponding to known faults rises to 27 percent. Although field checking confirmed only 4 new faults, two of which had been mapped independently by others, 5 other lineaments had trends parallel to sets of joints and/or shears observed on the ground. Field observations along 3 lineaments were inconclusive. The ground check supports inferences from rose diagrams and topographic expression that the lineaments we mapped are mainly controlled by fracture. A difficulty with our lineament map is the existence of a significant number of mapped faults for which no lineaments were annotated. These include thrusts and overthrusts, which have low angles of dip and are unlikely to be expressed topographically as straight lines. The reasons for other faults not being expressed as lineaments are unclear.

If thrusts and overthrusts are ignored, our lineament map gives a

good approximation of a fault map in representing most of the major faults and the general pattern of lesser faults. The map suggests different domains of homogeneous fracture patterns and structural style.

Expectations that the synoptic view provided by ERTS imagery and mosaics would clarify the obscure geologic map picture of the Lewis and Clark lines were not fulfilled. We see this zone, which appears to represent an inactive continental transform fault, as a band of short lines with northwesterly trends separating areas to the north and south of different lineament patterns.

We believe our mapped lineaments represent geologically significant lines, even for the many cases where the meaning of the lines is not understood. The map is analogous in some respects to certain geophysical maps. It can be used just as geophysical maps are used, to stimulate geologic thinking and perhaps to shed light on specific problems. We have made arrangements with the Montana Bureau of Mines and Geology to publish a version of the lineament map expanded to include eastern Montana.

Folds and Circular Structures

East of the continental divide elongate plunging folds larger than 3 miles in wave length may usually be delineated from ERTS imagery, and about half can be correctly identified as anticlines or synclines on the basis of dip directions. Dip direction is inferred from flatirons on parts of the larger folds and from ridge and drainage assymetry in other cases. Delineation of a major anticlinal nose demonstrated significant location and trend errors in a reconnaissance portion of the state geologic map (1.5 miles and 20°).

Some 40 circular structures ranging in diameter from 3 to 8 miles were delineated from ERTS imagery. Most are recognized as domes in sedimentary rocks. Shadow modelling reveals domal form directly in

some cases and through concentric ridge-valley patterns in others. The domes, which occur mainly east of the continental divide, are intrusive in origin (laccoliths and stocks). Forest cover present on some of the domes does not interfere with their recognition in ERTS imagery. We were alert to the possibility of discovering new impact structures and checked those circular structures which are not obviously domes using geologic maps and reports. We found no clues in the literature suggesting impact origins for any circular structures annotated from ERTS imagery. A field reconnaissance of a circular structure mapped in the northeast corner of the Idaho batholith suggested an obscure relation to volcanism.

Identification and Mapping of Rock Units

Attempts to distinguish areas underlain by major rock units of various compositions, map their contacts, and identify the units in terms of rock composition met with mixed success. Locally, some very precise mapping was done and significant errors in the state geologic map were discovered at two locations. Alluvium, the extent of glaciation in western Montana, and the borders of fill in Cenozoic basins can be identified and mapped with reasonable continuity and accuracy. However, mapping the late Precambrian Belt Supergroup in western Montana is not possible at all, and distinguishing granite in the western area can rarely be done without the help of ground or aerial photo truth. Under favorable circumstances volcanics can be delineated, but only if they are relatively undeformed and show contrasts with the surrounding terrane. It is possible to identify terranes of sedimentary strata of Paleozoic and Mesozoic age if the beds are tilted and eroded differentially; rocks of the two ages can often be distinguished on the basis of the greater resistance and forest cover of the Paleozoic carbonate sequences in contrast to the subdued topography and grassy vegetation of the Mesozoic strata. Recognition of a

few stratigraphic horizons within these sequences is possible locally where control from ground truth or aerial photos is available.

Mineral Resource Applications

Annotation of ERTS imagery for an area of known bentonite occurrences in the Bearpaw Shale northeast of Billings resulted in a map showing elongate patches of very light tone. These were known from previous study to represent highly reflective clay pans characteristic of the stratigraphic interval containing bentonite beds. The relationship suggests that ERTS imagery might be used to locate other areas of bentonite occurrance in the Bearpaw Shale of the Montana plains.

A possible application of ERTS imagery to petroleum geology is suggested by a dissertation investigation of the Montana Group for an area northwest of the Black Hills. Prior to the start of field and subsurface studies, a lineament map was drawn and used to delineate zones of lineament concentration which might represent the borders of basement blocks subject to differential tectonism through time, and hence capable of influencing sedimentation. Comparison of the lineament zones with geologic and aeromagnetic maps supported the assumption, and resulted in refined block boundaries. Stratigraphic studies suggest that the zones based on lineaments mark paleotectonic hinge lines where differential block movements influenced the position of progradational shale prisms and the distribution of bar and beach sands.

Possible relationships of known hydrothermal ore deposits in western Montana to lineaments, lineament density, lineament trends, and lineament intersections were evaluated by plotting mines and mining districts on our lineament map and by preparing a more generalized map of significant hydrothermal centers for quantitative comparison with the lineament map. Analysis shows that of 111 centers, 43 percent occur on lineaments, 48 percent occur in areas of high lineament den-

sity, and 10 percent occur at lineament intersections (high lineament density usually correlates with areas of Cretaceous granite and Pre-cambrian basement rock). Eleven cases were found where mines or hydrothermal centers of mineralization are distributed along trends parallel to lineaments, but half of these are located in one area, the eastern fringe of the Couer d'Alene mining district. Efforts to see tonal anomalies which might reflect hydrothermal alteration or the weathering of sulfide ore bodies were unsuccessful.

Interrelationships between hydrothermal centers and lineaments are not particularly striking, and there appear to be no simple ways of predicting probable locations of undiscovered hydrothermal centers from the lineament map alone. However, for areas suspected of being favorable sites on the basis of other geologic factors, the lineament map might be used to localize limited targets for reconnaissance exploration.

Landform Recognition

The study of landforms seen in ERTS imagery was not a stated objective of our investigation. However, because landforms were usually the most important characteristic used in our photogeologic interpretations, we are including some comment. The potential for using ERTS imagery for identifying landforms was far beyond our initial expectations. Recognition of major features such as fault scarps, mountain fronts, large uplifts in the plains area, and Cenozoic intermontane basins is easily accomplished. What surprised us was the widespread recognition of small landforms such as erosional and depostional features of alpine glaciation, and hogback ridges, flatiron dip slopes, cuestas, and escarpments formed by differential erosion of sedimentary strata. Recognition of the smaller landforms usually requires favorable illumination (low sun elevation) or the use of the stereoscope in areas of image sidelap.

Suggested Applications and Cost Benefits

For Montana, an area previously covered by a combination of detailed and reconnaissance geologic mapping on the ground, the most important geologic uses of ERTS imagery appear to be the preparation and analysis of tectonic maps, especially lineament maps. On such maps, the longer lines usually represent high-angle faults and the shorter lines lesser faults or trends of fracture sets (minor faults and joints). Most overthrusts and low-angle reverse-slip faults will not be represented by lineaments because of their low dip.

The pattern of lineaments may be interpreted in the same way as fracture patterns mapped from aerial photographs or on the ground. One use is the identification of structural domains representing areas of homogeneous fracture patterns in individual structural blocks. Another use is the delineation of zones of lineament concentration which may mark the boundaries of basement blocks on which differential movements through time may have generated paleotectonic hinge lines. Such lines control sedimentation and may be important in petroleum exploration. In tectonic map compilation longer lineaments not coincident with known faults should be regarded as strong indications of probable unmapped faults and carefully checked on aerial photographs or on the ground. To some extent, the lineament map of western Montana may be helpful in localizing exploration for hydrothermal ore deposits, provided other geologic conditions are favorable.

Other aspects of tectonic map preparation, particularly the delineation of folds caused by tectonic deformation and domes caused by igneous intrusion, can be accomplished cheaply and quickly using ERTS imagery for Montana east of the continental divide. However, such mapping would lack detail and be incomplete

in patches, especially where folds are small (less than a few miles wide) or lack plunge. Such mapping would best be done using existing geologic maps and aerial photographs. Nevertheless, our discovery of a significant location and trend error for a nose shown on the state geologic map demonstrates the possibility of using ERTS imagery to check fold delineation for places where better control is lacking.

The recognition and mapping of major rock units of different compositions from ERTS imagery, though possible to a degree, can be accomplished more reliably and in more detail using existing geologic maps supplemented by aerial photo interpretation. However, compilation and conventional aerial photo-interpretation are slow and relatively expensive procedures. In contrast, delineation of major rock contacts, when calibrated with aerial photo control tied locally to geologic maps, allows rapid and inexpensive reconnaissance mapping and the identification of errors in the existing state geologic map (1:500,000). Another potential application of ERTS photogeologic interpretation is the identification of areas containing bentonite beds in eastern Montana.

It is difficult to quantify the cost benefit of geologic uses of ERTS imagery in Montana. Lineament maps of local areas can be prepared by experienced operators in a few days time. A lineament map, useful as a substitute for a tectonic map in several important respects can be prepared for the entire state at a cost of only a few thousand dollars (if truth evaluations are not included). The total cost of a statewide lineament map is probably only a few percent of the cost of a compiled statewide tectonic map at the same scale. Additional benefits from use of lineament maps in fields such as geothermal, petroleum, and ore mineral exploration are expected to be significant.

When the geologic map of Montana is revised, ERTS imagery can be used to check for errors of omission and contact placement in those parts of the existing map drawn originally on a reconnaissance basis. Such a procedure requires only calibration of ERTS annotations for very limited areas using ground or map truth or aerial photographs. Lineaments drawn from ERTS imagery can be used as described above as guides to possible unmapped faults. The cost benefits of including these procedures in geologic map revision program should be significant.

A miscellaneous benefit is the use of ERTS imagery and mosaics as index maps in geologic reports. Not only do they show geographic locations, but they provide a general overview in image form which conveys information on such variables as topography, alpine glaciation, vegetation, geologic structure, and the distribution of certain rock units. For the reasons cited above, ERTS imagery is also a powerful tool in geologic education.

There are significant geologic applications and costs benefits for Montana, despite the fact that the state has previously been completely covered by detailed or reconnaissance geologic mapping. For geologically less studied areas of roughly comparable latitude topography, climate, and geologic terranes elsewhere in the world, applications and cost benefits would be enhanced manyfold. For such areas we would expect to be able to prepare a somewhat spotty but very useful and inexpensive photogeologic reconnaissance map at a scale as large as 1:500,000. The map would show alluvium, the extent of Pleistocene alpine glaciation, sediment filled Cenozoic intermontana structural basins, differentially eroded sedimentary rock sequences and young volcanic fields. With some control from aerial photographs, the more difficult reconnaissance mapping of granitic bodies and metamorphic basement rock would be possible for some cases. Structural fea-

tures mapped from ERTS imagery alone would include major uplifts, folds, and faults, as well as many of the smaller fold and dome structures, including some as small as two miles in width. General structural style would be apparent from inspecting the photogeologic map and a separate lineament map. Expected omissions would include many or most overthrust and thrust faults, and most folds for forest covered areas of homogeneously resistant strata such as the Belt terrane of western Montana.

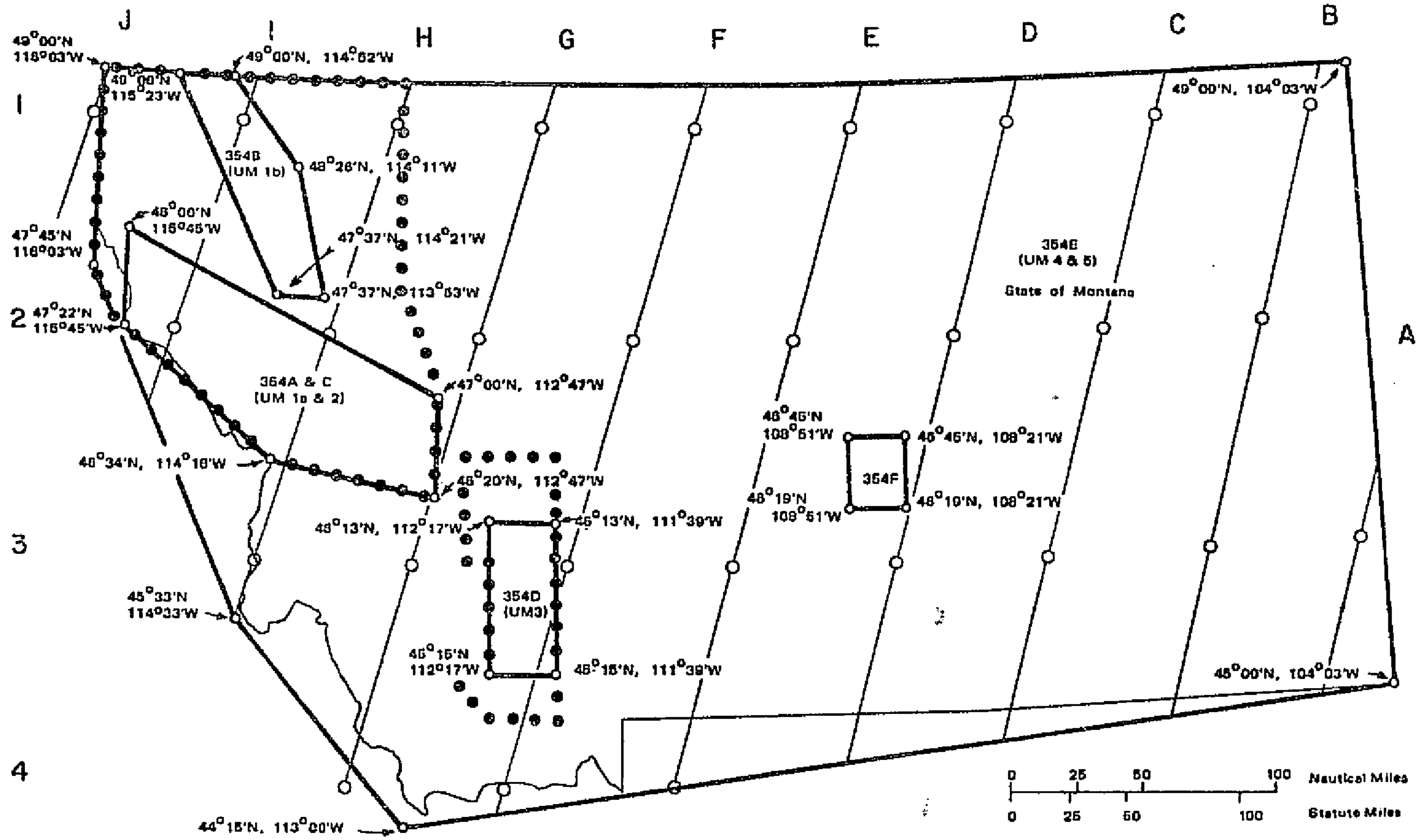


Figure 23. Index map showing Montana test sites and ERTS-1 nominal orbital paths and scene centers. Test Sites 354 A & C, B, and D were covered by NASA-ERAP Flight No. 72-125 (26 July 1972) and reflown in part by Flight No. 74-140 (16 August 1974). Test Site 354 F was photographed during part of Flight 72-138 (11 August 1972). Sensors on these U-2 flights were the Vinten System (70mm multispectral) and the RC-10 metric camera (Aerochrome Infrared 2443). Dotted lines show expanded test sites for lineament evaluation.

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